CLASS VI PERMIT TESTING AND MONITORING PLAN

40 CFR 146.90 & LCFS Protocol Subsection C.4.1(a)

STRATEGIC BIOFUELS
LOUISIANA GREEN FUELS PORT OF COLUMBIA FACILITY

Prepared By:
GEOSTOCK SANDIA, LLC

Revision No. 0
February 2023

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1.0 FACILITY INFORMATION

Facility Name:	Louisiana Green Fuels, Port of Columbia Facility Three Class VI Injection Wells
Facility Contact:	Bob Meredith, COO 303 Wall St., Caldwell, LA 71418 (318) 649-6401 bob.meredith@strategicbiofuels.com
Well Locations:	Port of Columbia, Caldwell Parish, Louisiana **Name: Latitude / Longitude** Well 1 (W-N1): 32.18812141510 / -92.10986101060 Well 2 (W-N2): 32.18686691570 / -92.05915551900 Well 3 (W-S2): 32.1639375970 / -92.08754320370

This *Testing and Monitoring Plan* describes how the Louisiana Green Fuels, Port of Columbia Facility will monitor the sequestration project pursuant to USEPA 40 CFR §146.90 and the Carbon Capture and Sequestration (CCS) Protocol under the California Air Resources Board (CARB) Low-Carbon Fuel Standard (LCFS) (Subsections C.2.5 and C.4.3.2.2; CARB, 2018). This plan also meets the requirements of the *Monitoring, Measurement, and Verification Plan* required under LCFS Subsection C.4.3.2.

In addition to demonstrating that the injection wells are operating as expected, that the carbon dioxide plume and pressure front are moving as predicted, and there is no endangerment to underground sources of drinking water (USDWs), the monitoring data will be used to validate and guide any required adjustments to the geologic and dynamic models used to predict the distribution of carbon dioxide within the storage complex, supporting Area of Review evaluations and a non-endangerment demonstration. Additionally, the testing and monitoring components include a leak detection plan to monitor and account for any movement of the carbon dioxide outside of the storage reservoir.

In accordance with 40 CFR §146.90 (j) and LCFS Protocol Subsection C.4.1(a)(16) this testing and monitoring plan will be re-evaluated every 5 years (at a minimum) or more frequently at the direction of the underground injection control (UIC) Director. The review process will evaluate whether the current plan will require an amendment. All amendments will be approved by the UIC Director and incorporated into the currently authorized operating permit.

Results of the testing and monitoring activities described below may also trigger response actions according to the Emergency and Remedial Response Plan [40 CFR 146.94(a)] and LCFS Protocol Subsection C.6.1.

2.0 OVERAL STRATEGY AND APPROACH

This Testing and Monitoring Plan is adapted to Port of Columbia Facility area and considers the following site-specific strategy and approach:

- The primary injection zone is comprised of the Tuscaloosa/Paluxy Formation, which consists of a stacked package of porous and permeable sandstone that are separated by local clay/shale baffles. The shallower Annona Sandstone, which is located approximately 700 feet above the top of the Tuscaloosa Formation, may also be used as a separate sequestration interval, should additional capacity be needed for the facility. Near the facility, the Annona Sandstone is a blanket sand that has a minor clay/shale baffle in the middle of the package. These two Injection Zones will act as separate flow units and are separated by approximately 700 feet of tight, impermeable and argillaceous chalks. The Annona Sandstone, in turn, is overlain by approximately 300 feet of Upper Cretaceous chalks (Selma Chalk).
- The performance of both the multiple sandstones of the upper Tuscaloosa/Paluxy Formation and the Annona Sandstone of the Selma Formation in accepting injection fluids is well known. Each interval has been injection tested to compute transmissibility (permeability-thickness/viscosity) in the Whitetail Operating, LLC, Louisiana Green Fuels #1 (stratigraphic test well). Test fluids consisted of municipal water mixed with a clay stabilizing surfactant. Additionally, the Lower Tuscaloosa Formation has hosted an extensively monitored DOE-funded sequestration injection project at the Cranfield Oil Field near Natchez, Mississippi, and has also been the primary reservoir targeted by tertiary carbon dioxide enhanced oil recovery in multiple oil producing fields by Denbury Resources.
- The project area is free of faulting at seismic resolution. A number of reprocessed two-dimensional seismic lines are located across the immediate project area and were used in the site characterization work. Interpretation of the data indicates that there is no faulting across either the Injection Zone or the Confining Zone (i.e., the Sequestration Complex).
- The Paleocene Midway Shale is of regional extent and forms the Confining Zone for the Project. The Midway Shale is approximately 700 feet thick beneath the Port of Columbia Facility, forming an impermeable top seal to the sequestration complex. The ductile

Midway Shale is free of transecting faults in the area and has the lithologic properties to limit vertical fracturing in the subsurface.

- The Eocene Wilcox Formation overlaying the Midway Shale is composed of approximately 1,300 feet of highly transmissive sandstones that are interbedded with regionally extensive shales and local mudstone baffles. In the northeast Louisiana area, the multiple sandstones of the Wilcox Formation typically contain saltwater. In certain limited areas minor volumes of thermogenic methane, generated from thin lignite beds developed predominantly within the Lower Wilcox, have been encountered trapped within thin Wilcox channel sands. In addition, minor volumes of methane have been produced from two of the lignite source beds, which are also called "coalbed methane" reservoirs in the Caldwell Parish area. Small coalbed methane gas fields such as the Riverton Field that overlies the Port of Columbia Facility area were initially drilled 20-30 years ago and have since been either shut in or abandoned. Wilcox sandstones have also been utilized for Class 1 injection of effluents (predominantly brine produced as a consequence of oilfield production) in East Louisiana and Southwest Mississippi. The thick sand/shale sequence of the Wilcox Formation thus serves as a series of alternating saline buffer aquifers and impermeable shales positioned between the top of the Sequestration Complex and the lowermost underground source of drinking water (USDW). As such, this thick sand/shale sequence serves to further limit vertical fluid movement and allow for the dissipation of pressure from any extraneous injectate that may reach the top of the Confining Zone.
- The Sparta aquifer is well known as a groundwater resource in northern Louisiana. It is separated from the underlying Wilcox Formation by the Cane River and Tallahatta Formations, both of which are confining zones. The Cane River Formation is an impermeable clay/shale and confines the overlying Sparta aquifer from the underlying Wilcox Formation. The Tallahatta is comprised of an interlaminated series of marls, hard quartzitic lenses, and calcareous clay/shales that are typically poor in porosity and permeability, which also acts as a confining layer.
- Natural seismicity in the area is exceedingly low, with no recorded historical earthquakes in either Caldwell Parish or the immediately adjacent parishes. The closest recorded earthquakes are located more than 125 kilometers away from the Port of Columbia Facility, near the Arkansas-Louisiana State Line. Induced seismicity risk is also low due to the lack

of any nearby faults and because of high transmissivity in the Tuscaloosa/Paluxy and/or Annona Injection Zones. Previous measurements of induced seismicity in Department of Energy supported research projects along the Gulf Coast (Mississippi Cranfield Project, for example), have not detected events resulting from the injection of large volumes of carbon dioxide. Therefore, regional seismicity will be monitored annually using public sources for any change in occurrence or frequency of seismic events. Only if a change in frequency occurs, will additional site-specific monitoring of local events be undertaken by the Port of Columbia Facility.

- Surface and near-surface monitoring at the Port of Columbia Facility is designed to be responsive to the near-surface setting. The area is dominated by complex surface conditions including tree and grass-dominated high areas, intermittently flooded freshwater wetland, and riparian zones. The area is expected to be dynamic in terms of seasonal carbon dioxide production and uptake from active environments, including wetland bottom sediments, intermittently saturated soils, plant and animal activities, and other activities which are likely to change over time. The determination of the baseline spatial distribution of atmospheric and soil gas monitoring stations will be determined on a site-specific basis and will consist of repeat measurements at several fixed and variable sites, and over a period of at least one year, to capture any seasonal or diurnal variations (LCFS Protocol Subsection C.4.1).
- The five proposed injection wells will create a composite carbon dioxide plume and a single area of elevated subterranean pressures underlying the active facility. Both the carbon dioxide plume and the Area of Review perimeter will grow over time and the expanding plume has the potential to intersect existing (legacy) wells. Validation of the magnitude and area of pressure increase during injection is, therefore, a monitoring focus, as is documenting the extent of the carbon dioxide plume through stabilization during the post-injection monitoring period.

The proposed monitoring network for the project is composed of the following elements, listed from deepest and closest to the point of injection, to the furthest away and shallowest. The overall concept for the monitoring program is presented in Figure 1 and project monitoring well locations are shown in Figure 2.

In-Zone Monitoring (IZMI Monitoring)

Direct Monitoring

- In-zone monitoring at the injection wells will assure that the wells are performing as intended, which is to deliver the carbon dioxide to the subsurface storage intervals (Injection Zone), and measure the pressure response in the reservoir intervals, a key model match parameter. Downhole pressure gauges and injection logging in the constructed injection wells will be used to collect real-time, continuous data that will be used to assess reservoir response to injection (LCFS Protocol Subsection C.2.5(b)(2)). Gauges will be referenced to ground level at each well.
- In-zone pressure (IZ) monitoring wells will validate the model of growth of sequestered carbon dioxide plume and the growth of the Area of Review over time. Real-time, continuous IZ pressure-monitoring will be performed initially be outside of the carbon dioxide plume. Monitoring will leverage the recently drilled and tested Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well (SN975841), located approximately 5,273 feet southeast of the proposed injection wells. Additionally, the following offset wells will be reentered and converted to monitoring wells:
    - Bradford-Brown Trust Shipp No. 1 (SN137783) well, located approximately 10,152 feet north and up dip of the facility;
    - Bass Keahey No.1 (SN165395) well, located approximately 13,730 feet northeast and up dip of the facility;
    - Southern Carbon USA No. 1 (SN34225) well, located approximately 37,850 feet east- southeast of the facility; and
    - Murphy Meredith No. 1 (SN23356) well, located approximately 28,150 feet east-southeast of the facility.

  Each well will be re-entered and repurposed for monitoring (deepening and completion of the well) across the entire Tuscaloosa/Paluxy Sandstone. At a minimum, each well will be fitted with a downhole pressure/temperature gauge (gauge will be referenced to ground level). During recompletion, native Tuscaloosa/Paluxy formation water will be sampled initially upon monitoring well construction/completion (including for dissolved and free gases) for baseline characterization purposes per LCFS Protocol Subsection

C.2.3(a)(9)(A). Note that baseline sampling and analyses have already been completed in the Whitetail Operating, LLC, Louisiana Green Fuels #1 (SN975841) well.

These In-zone monitor wells will also provide direct measurement, when or if, the sequestered carbon dioxide plume ever reaches the monitoring well location (LCFS Protocol Subsection C.2.5(b)(2)). Should the monitoring wells begin to show the presence of carbon dioxide (either by change in downhole pressure and temperature or by surface pressure and temperature), an adaptive fluid sampling program will be triggered in the affected well(s). Work will be conducted by a qualified vendor and the selected analytical laboratory will be compliant with the Louisiana Environmental Laboratory Accreditation Program[1]. Once carbon dioxide is detected at a well, it will be plugged back and repurposed for indirect monitoring or will be permanently plugged.

Indirect Monitoring

- Indirect monitoring will be used to assess the performance of the Sequestration Complex to ensure that it is operating as intended. Indirect plume monitoring will be employed in the injection wells and the "in zone" monitoring wells to define the location, extent, and thickness of the sequestered carbon dioxide. Pulsed neutron capture logs will be used to monitor carbon dioxide saturation at the injection wells and in the two Tuscaloosa/Paluxy Injection Zone Monitoring Wells, once carbon dioxide is detected or determined to be in close proximity to the wells. Saturation logging in the two Tuscaloosa/Paluxy Injection Zone Monitoring Wells will help in understanding the larger scale flow distribution in the Tuscaloosa/Paluxy away from the Port of Columbia Facility.

  The areal distribution of the carbon dioxide plume in the Tuscaloosa/Paluxy Injection Zone will be determined using time-lapse seismic techniques. Substitution of carbon dioxide for brine within sandstones, such as the Tuscaloosa/Paluxy Formation, at similar project depths is well documented to produce a strong change in acoustic impedance (Vasco et al., 2019). Leading-edge techniques for time-lapse imaging of carbon dioxide plumes developed during implementation of the Regional DOE Partnership projects include time-lapse vertical seismic profiling (Daley and Korneev, 2006; Gupta, et al., 2020), azimuthal

[1] https://deq.louisiana.gov/page/la-lab-accreditation

vertical seismic profiling (Gordon, et al., 2016), and sparse array walk-away surveys or scalable, automated, semipermanent seismic array "SASSA" (Roach, et al., 2015; Burnison, et al., 2016; Livers, 2017; Adams, et al., 2020).

At a minimum, during the acquisition of walk-away vertical seismic profiling and sparse array walk-away surveys, the array of acoustic source sites will be oriented along the maximum and minimum orientations of the modeled plume and will be adjusted following a review of the results of each survey. Survey frequency will be dependent on the monitoring method chosen and reevaluated after each survey (adaptive program). It is expected that for walk-away vertical seismic profiling g and sparse array walk-away techniques, frequency will be an initial baseline survey, followed by repeat surveys at the end of 1 year, 3 years, 5 years, and then every 5 years thereafter.

Above-Zone Monitoring (AZMI Monitoring)

- Above Zone Monitoring Interval (AZMI) monitoring will occur in wells installed in areas where In-zone monitoring will be occurring. The AZMI Monitoring zone for the sequestration project is the Annona Sandstone. The Annona Sandstone is a blanket sand that extends throughout the Area of Review. IZ Monitoring and AZMI Monitoring wells are expected to be engineered as multi-zone completions, if feasible. The Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well (SN975841), located 5,273 feet southeast of the injection wells, and the Bradford-Brown Trust Shipp No. 1 (SN20131) well, located approximately 10,152 feet up dip of the injection wells, will be engineered for both IZ and AZMI Monitoring.

  In the AZMI Monitoring zone, each well will be fitted with real-time, continuously recording downhole pressure/temperature gauge (LCFS Protocol Subsection C.2.5(b)(2)). Gauges will be referenced to ground level at each well. Alternately, a "light" fluid column to allow monitoring and recording pressures at surface will be used. Native formation water in the Annona Sandstone will be sampled initially upon well construction (including for dissolved and free gases) for baseline characterization purposes (sampling and analyses have been completed in the Whitetail Operating, LLC, Louisiana Green Fuels #1) per LCFS Protocol Subsection C.2.3(a)(9)(B). A native formation water will be sampled initially (including for dissolved and free gases) for baseline characterization purposes in

the repurposed Bradford-Brown Trust Shipp No. 1 (SN20131) well during recompletion operations.

Changes in water composition are not expected in the AZMI Monitoring zone. However, these AZMI Zone Monitor wells will provide direct measurement if fluid movement out of Tuscaloosa/Paluxy Injection Zone occurs. Should either monitor well detect the presence of carbon dioxide (either by change in downhole pressure and temperature or by surface pressure and temperature), an adaptive fluid sampling program will be triggered and initiated. Sampling work will be conducted by a qualified vendor and the selected analytical laboratory will be compliant with the Louisiana Environmental Laboratory Accreditation Program.

Above-Confining Zone Monitoring (ACZMI Monitoring)

- Above Confining Zone Monitoring Interval (ACZMI) monitoring will occur in a well drilled and completed in the basal Wilcox on the Port of Columbia Facility property (LCFS Protocol Subsection C.2.5(b)(2)). The initial ACZMI Monitoring zone for the sequestration project is a porous Wilcox sandstone located at a depth of 2,846 to 2,866 feet below ground level (as stratigraphically referenced to the Southwestern Energy Production Company CPC #1 well (SN235656), located near the southeastern corner of the facility property) that is located stratigraphically just above the top of the Midway Shale. The ACZMI Monitoring well shall be located near the point of carbon dioxide injection, where elevated formation pressure in the Tuscaloosa/Paluxy would be the greatest.

  The ACZMI well will be monitored with real-time, continuously recording downhole pressure/temperature gauge. The gauge will be referenced to ground level. Native formation water will be sampled initially upon well construction (including for dissolved and free gases) for baseline characterization purposes. An initial baseline characterization of the lower Wilcox will be performed per LCFS Protocol Subsection C.2.3(a)(9)(B). Quarterly baseline sampling will be performed for at least one year prior to injection of carbon dioxide per LCFS Protocol Subsection C.2.5(b)(c)(d)(e). The well will be monitored quarterly following initiation of injection of carbon dioxide for any changes in water quality and composition. An adaptive fluid sampling program will be initiated with

more frequent monitoring events should indications of carbon dioxide be suspected. Field sampling work will be conducted by a qualified vendor and the selected analytical laboratory will be compliant with the Louisiana Environmental Laboratory Accreditation Program.

Underground Sources of Drinking Water Monitoring (USDW Monitoring)

- Aquifers in the area consist of the shallow Mississippi River Alluvial Aquifer, the mid-depth Cockfield Aquifer, and the deeper Sparta Aquifer. Public water supply in the area is supplied by the East Columbia Water District with supply from the Mississippi River Alluvial Aquifer and the Cockfield Aquifer. The Louisiana Department of Health routinely monitors for constituents in the drinking water according to Federal and State laws. The Port of Columbia Facility will secure split samples from the municipal water wells when they are sampled by the East Columbia Water District. These samples will be used to establish the baseline per LCFS Protocol Subsection C.2.5(b)&(c)&(d)&(e) and will be monitored for any indicated long-term changes in measured parameters. An adaptive fluid sampling program will be initiated with more frequent monitoring events in the freshwater aquifer should indications of carbon dioxide be detected in the Basal Wilcox (via the ACZMI Monitor Well).

Surface and Near-surface Monitoring

- Atmospheric monitoring across the Area of Review will be conducted utilizing a single, broad-range eddy covariance system and a portable gas meter to define natural background variability, including seasonal and diurnal trends, and to detect potential atmospheric carbon dioxide leakage and/or potential movement of carbon dioxide that may endanger the local USDW (LCFS Protocol Subsection C.4.3.2.2(a)). An ecosystem and land-use survey based on satellite imagery analysis and focused ground-based vegetation surveys will be conducted over the surface projection of the Area of Review and pre-determined reference areas to establish background vegetative conditions at the surface and to measure potential stress resulting from elevated carbon dioxide in soil. Limited soil gas monitoring at up to 15 representative locations throughout the surface projection of the Area of Review

will be conducted to define the baseline molecular and isotopic compositions of the shallow soil gas, characterize natural background variability, including seasonal and diurnal trends, and to serve as reference and comparison to operational soil gas monitoring, if needed, to assist in the detection, validation, and quantification of potential carbon dioxide leakage (LCFS Protocol Subsection C.4.3.2.2(b)).

2.1 QUALITY ASSURANCE PROCEDURES

A quality assurance and surveillance plan (QASP) for all testing and monitoring activities, required pursuant to §146.90(k), is provided in Appendix 1 – Quality Assurance and Surveillance Plan (QASP) to this Testing and Monitoring Plan.

2.2 MONITORING DETAILS

The Louisiana Green Fuels, Port of Columbia Facility will sample and record injection and monitoring operations using a SCADA distributive control system (or similar). Operations will be monitored at a central Control Room and data will be recorded in real-time. An archiver may be used to reduce the data stream size for longer term data storage. The distributive control system will consist of safe-set controls and alarms at values safely below regulatory requirements so that permit limits are not exceeded. All gauges and equipment will be calibrated per manufacture's specifications and calibration records will be maintained at the facility.

2.3 REPORTING PROCEDURES

The Louisiana Green Fuels, Port of Columbia Facility will report the results of all testing and monitoring activities to the Executive Director in compliance with the requirements under 40 CFR §146.91 and LCFS Protocol Subsection C. 1.1.3. Table 1 is an overview of the frequency and monitoring for each monitoring activities identified within this Testing and Monitoring Plan for the Louisiana Green Fuels Port of Columbia Facility.

Table 1: Testing and Monitoring Reporting Overview

Parameters Monitored	Monitoring Program	Monitoring & Reporting Frequency [a]
Carbon Dioxide Stream Analysis [40 CFR §146.90(a)] & LCFS Subsection C. 4.3.1.1.		

Parameters Monitored	Monitoring Program	Monitoring & Reporting Frequency [a]
Chemical and Physical Composition of CO_2 Stream	Compositional analysis of the injected CO_2 stream using non-destructive Chromatographic detector	Quarterly or as process changes or additional sources are included in the injection stream.
Continuous Recording of Operational Procedures [40 CFR §146.88(e)(1), §146.89(b), and §146.90(b).] & LCFS Subsection C. 4.1(a)(2)		
Injection Parameter Monitoring	Pressure and temperature gauge, mass flow meter with alarms for measurements outside of the normal operating conditions	Continuous monitoring. Summary Monthly statistics prepared and reported quarterly.
Annulus Pressure Monitoring	Annulus pressure gauge	
	Annular Fluid Volume Measurements	
Corrosion Monitoring [40 CFR §146.90(c)] & LCFS Subsection C. 4.1(a)(3)		
Coupon Testing	Flow-through corrosion coupon using injection well construction materials Utilize Corrosion inhibitors in all fluids during well workovers	Quarterly analysis during injection operations. Additionally, as new sources added to stream
In-Zone Tuscaloosa/Paluxy Monitoring – IZ Monitoring - 2 Wells		
Tuscaloosa/Paluxy Sand	Temperature, Pressure fluid analysis only if triggered by pressure or temperature signal	Continuous real time Pressure Monitoring Fluids samples on an as needed basis
Tuscaloosa/Paluxy Sand	Water analysis (if triggered)	Quarterly analysis during injection operations. Annually during post-injection operations.
Above Tuscaloosa/Paluxy Monitoring -AZMI (Annona Sand Monitoring) – 2 Wells [LCFS Protocol Subsection C.2.5(b)(2)]		
Annona Sand	Temperature, Pressure fluid analysis only if triggered by pressure or temperature signal	Continuous real time Pressure Monitoring Fluids samples on an as needed basis
Annona Sand	Water analysis	Quarterly analysis during injection operations. Annually during post-injection operations.

Parameters Monitored	Monitoring Program	Monitoring & Reporting Frequency [a]
Above Confining Zone Monitoring ACZMI - [40 CFR §146.90(d) and §146.90(f)(3) & (LCFS Protocol Subsection C.2.5(b)(2))]		
Wilcox Formation above Confining Zone	Temperature, Pressure fluid analysis on a quarterly basis and adaptive if triggered by pressure or temperature signal	Continuous real time Pressure Monitoring Fluids samples on a quarterly basis
USDW Monitoring [40 CFR §146.90(d)]		
USDW Monitoring Well (Public Water Supply)	Water analysis	Minimum quarterly analysis during injection operations. Annually during post-injection operations.
External Mechanical Integrity [40 CFR §146.89(c) and §146.90] & LCFS Protocol Subsection C.4.2(a)&(b)		
Well Integrity	Annulus Pressure Tests, Radioactive Tracer Survey, Temperature Survey	Annually and after all well workover operations that change well configuration.
Pressure Falloff Test [40 CFR §146.90(f)] & LCFS Protocol Subsection C.2.3.1(i)(1)		
Reservoir transmissivity and pressure.	Pressure Falloff Test, Static and Flowing Bottomhole Pressures	Baseline test after well completion. Annual Years 1 to 5. Every 5-years thereafter.
CO2 Pressure and Plume Front [40 CFR §146.90(g)] & LCFS Protocol Subsection C.4.1(a)(9)(A)		
Two Tuscaloosa/Paluxy Monitor Wells	Direct Pressure Monitoring	Continuous
Injection Wells Pulsed Neutron Logging Repeat Seismic	Indirect Monitoring	Baseline, 1 year, 3 years, 5 years, and then every 5 years thereafter
Atmospheric Monitoring [40 CFR §146.90(h); CARB LCFS Protocol Subsections C.2.5(c)(d) and C.4.3.2.2(d)(e)]		
Atmosphere, continuous	Eddy Covariance Tower (fixed location): • CO_2, CH_4, H_2O, and N_2O concentrations; • Net CO_2 flux across ecosystem within tower footprint; • Wind direction and speed; • Soil conditions (i.e., moisture, temperature, and heat flux);	Continuous monitoring during baseline and injection.

Parameters Monitored	Monitoring Program	Monitoring & Reporting Frequency [a]
	• Net radiation across surface; • Meteorological conditions (i.e., relative humidity, barometric pressure, ambient temperature, and precipitation)	
Atmosphere, intermittent	Landfill Gas Meter (variable locations): CO_2, O_2, and CH_4 concentrations	Baseline: Monthly Injection: Quarterly
Ecosystem Stress Monitoring [40 CFR §146.90(h); CARB LCFS Protocol Subsections C.2.5(c)(d) and C.4.3.2.2(f)]		
Ecosystem Stress	Satellite Imagery (site-wide)	Baseline: Single analysis (3 yr retrospective from end of baseline) Injection: Annually
Soil Gas Monitoring [40 CFR §146.90(h); CARB LCFS Protocol Subsections C.2.5(c)(d) and C.4.3.2.2(g)]		
Soil Gas, intermittent	Soil Gas Probes (fixed locations) Molecular Composition: CO_2, CH_4, N_2, and O_2 concentrations; C1-C5 hydrocarbons	Baseline: Monthly Injection: Quarterly
	Soil Gas Probes (fixed locations) Isotopic Composition: $\delta^{13}C$ and C^{14} of CO_2 and CH_4; δD of CH_4	Baseline: Quarterly Injection: Quarterly

[a] Data archiver may be used to reduce data streams

3.0 CARBON DIOXIDE STREAM ANALYSIS

The Louisiana Green Fuels, Port of Columbia Facility will analyze the composite carbon dioxide stream during the operational period to yield data representative of its chemical and physical characteristics and to meet the requirements of 40 CFR §146.90(a), LAC §3625.A.1 (State of Louisiana), and LCFS Protocol Subsection C.4.1(a)(1). A baseline sample of the carbon dioxide stream will be evaluated and tested prior to initiation of injection operations at the facility.

3.1 CARBON DIOXIDE SAMPLING LOCATION AND FREQUENCY

The injected carbon dioxide will be continuously monitored at the surface for pressure, temperature, and flow volumes. Sampling will be performed upstream or downstream of the flowmeter. Sampling procedures will follow protocols to ensure the sample is representative of the injected carbon dioxide stream.

The frequency of carbon dioxide sampling will be conducted on a quarterly basis commencing with the initiation of injection operations. This equates to a schedule as follows:

1. Sample No. 1: 3 months after start of injection
2. Sample No. 2: 6 months after start of injection
3. Sample No. 3: 9 months after start of injection
4. Sample No. 4: 12 months after start of injection

The schedule will then repeat using this quarterly sample cycle. When known changes to the injected stream occur (*i.e.*, source changes and/or additions/deletions to the existing stream), sampling will also be performed for verification of the chemical and physical properties of the modified stream. This will determine if there are changes to the stream that need to be accounted and tested for to update and compare to the baseline conditions. The proposed sample frequency is sufficient to characterize the carbon dioxide stream and account for any potential changes to a representative data.

Density measurements at the mass flow meter greater than normal variability and not correlated to thermal variations also will trigger sampling of the injection stream. The isotopic composition of

carbon in CO_2 ($\delta C^{12}/C^{13}$) ratio and C^{14} will be measured for baseline and repeated only if new sources are added.

3.2 CARBON DIOXIDE ANALYTICAL PARAMETERS

The Louisiana Green Fuels, Port of Columbia Facility will contract a vendor to analyze the carbon dioxide for the constituents identified in Table 2 using the methods listed (or equivalent). If the constituents are not found in initial analysis or are screened out at the source prior to injection, this will be documented and with the prior approval of the UIC Program Director, they will be removed from the list of analytical parameters.

Table 2: Summary of analytical parameters for CO_2 stream.

Parameter	Analytical Method(s)[1]
Carbon Dioxide (CO_2)	ISBT[2] 2.0 Caustic absorption Zahm-Nagel ALI method SAM 4.1 subtraction method (GC/DID) GC/TCD
Oxygen (O_2)	ISBT 4.0 (GC/DID) GC/TCD
Nitrogen (N_2)	ISBT 4.0 (GC/DID) GC/TCD
Hydrogen Sulfide (H_2S)	ISBT 14.0 (GC/SCD)
Sulfur dioxide (SO_2)	ISBT 10.1 (GC/FID)
Methane (CH_4)	ISBT 10.1 (GC/FID)
Total hydrocarbons (C_2H_6, C_3H_8+)	ISBT 10.0 THA (FID)
Hydrogen (H_2)	ISBT 4.0 (GC/DID) GC/TCD
Carbon Monoxide (CO)	ISBT 5.0 Colorimetric ISBT 4.0 (GC/DID)
Nitrogen Oxides (any (NO_x)	ISBT 7.0 Colorimetric
Carbon isotopic composition δC^{13} and C^{14}	Measured once and when a significant new source is added. Used for attribution during monitoring

Note 1: *An equivalent method may be employed with the prior approval of the UIC Program Director, such as ASTM Standards*

Note 2. *International Society of Beverage Technologists (ISBT) Carbon Dioxide Guidelines MBAA TQ vol. 39, no. 1, 2002, pp. 32-35 as cited in ISO/TR 27921:2020(en). Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO_2 stream composition*

3.3 CARBON DIOXIDE SAMPLING METHODS

Sampling will be performed from a tap located upstream or downstream of the flowmeter and

will follow protocols to ensure the sample is representative of the injected carbon dioxide stream. Sample collection procedures will be provided in detail by a certified laboratory vendor to be determined prior to injection authorization. Sampling methods and equipment will meet the standards and limits provided provide within the attached QASP.

3.4 CARBON DIOXIDE ANALYSIS PROCEDURES AND CHAIN OF CUSTODY

Samples will be analyzed by a third party laboratory accredited by the Louisiana Department of Environmental Quality (https://internet.deq.louisiana.gov/portal/divisions/lelap/accredited-laboratories) using standardized procedures for gas chromatography, mass spectrometry, detector tubes, and photo ionization. Detection limits will be dependent on equipment facilitated for the analytical methods by the selected qualified vendor. However, all vendors will meet the minimum levels set forth in the QASP (Appendix 1).

The sample chain-of-custody procedures will be dependent on Vendor selection as they will assume the custody of the samples. The procedures will document and track the sample transfer to laboratory, to the analyst, to testing, to storage, to disposal (at a minimum). A sample chain of custody procedures is contained in the QASP (Appendix 1).

4.0 CONTINUOUS RECORDING OF OPERATIONAL PROCUDURES

The Louisiana Green Fuels, Port of Columbia Facility will install and use continuous recording devices to monitor injection pressure, injection rate (mass flow), and volume; the pressure on the annulus between the tubing and the long string casing; the annulus fluid volume added; and the temperature of the carbon dioxide stream, as required at 40 CFR §146.88(e)(1), §146.89(b), and §146.90(b) (State of Louisiana Guidance §3621.A.6.a, 3627.A.2, and 3625.A.2), and LCFS Protocol Subsection C.4.1(a)(2) and LCFS Protocol Subsection C.4.3.1.2.

Injection rates and pressures will be set by permit. All aspects of the injection processes will be monitored, recorded, and if necessary, shut down in the event of a detected exceedance. Surface pressure and temperature will be measured continuously. The volume will be determined from a mass flow meter installed on the injection supply line.

4.1 MONITORING LOCATION AND FREQUENCY

The Louisiana Green Fuels, Port of Columbia Facility will perform the activities identified in Table 3 to monitor operational parameters and verify internal mechanical integrity of the injection well. All monitoring will take place at the locations and frequencies shown in Table 3.

Table 3: Sampling devices, locations, and frequencies for continuous monitoring

Parameter	Device(s)	Location	Min. Sampling[1] Frequency	Min. Recording[2] Frequency
Injection Pressure (surface)	Pressure Gauge	Wellhead/Flowline	1 minute	30 minutes
Injection Pressure (downhole)	Quartz Pressure Gauge	Near Perforations	1 minute	30 minutes
Injection Rate	Mass Flow Meter/Computer	Flowline	1 minute	30 minutes
Injection Volume	Mass Flow Meter/Computer	Flowline	1 minute	30 minutes
Annulus pressure	Pressure Gauge	Wellhead	1 minute	30 minutes
Annulus fluid volume	Fluid Level Measure	Annulus Tank	1 minute	Daily
CO_2 stream temperature	Mass Flow Meter/Computer	Wellhead/Flowline	1 minute	30 minutes

Parameter	Device(s)	Location	Min. Sampling[1] Frequency	Min. Recording[2] Frequency
Downhole Temperature	Temperature Gauge	Near Perforations	1 minute	30 minutes
If Deployed on Injection Wells				
Changes in *Rayleigh* scattering resulting from distributed strain indicative of wave arrival	DAS optical fiber	Installed on outside of casing	As designed for acoustic survey	As designed for acoustic survey
Changes in *Rayleigh* scattering indicative of temperature change	DAS optical fiber	Installed on outside of casing	Hourly	Daily

[1] *Sampling frequency refers to how often the monitoring device obtains data from the well for a particular parameter. For example, a recording device might sample a pressure transducer monitoring injection pressure once every two seconds and save this value in memory.*

[2] *Recording frequency refers to how often the sampled information gets recorded to digital format (such as a computer hard drive). For example, the data from the injection pressure transducer might be recorded to a hard drive once every minute. Note a data archiver may be used to reduce data stream size for long term storage.*

Continuously recorded injection parameters will be reviewed and interpreted on a regular basis, to evaluate the injection stream parameters against permit requirements. Trend analysis will also help evaluate the performance (*e.g.*, drift) of the instruments, suggesting the need for maintenance or calibration.

Basic calibration standards, precision, formulas, conversion factors, and tolerances for measuring devices and analysis are included in the attached QASP but will be dependent on specific qualified vendor selection. Calibrations will be per manufacturers specifications and frequency.

4.2 MONITORING DETAILS

For each of the parameters that are required to be continuously monitored, such as injection pressure, injection rate, injection volume, annular pressure, annulus fluid volume, and carbon dioxide stream temperature, these will be monitored and recorded using a SCADA distributive control system (DCS) or similar. Results of the monitoring activities will be submitted to EPA in a semi-annual report for each of the following parameters:

- Monthly average, maximum, and minimum values for injection pressure, flow rate, and volume [40 CFR §146.91(a)(2)].

- Monthly average, maximum, and minimum values for annulus pressure [40 CFR §146.91(a)(2)].
- A description of any event that exceeds operating parameters for annular pressure or injection pressure specified in the permit, in compliance with [40 CFR §146.91(a)(3)].
- A description of any event that triggers a shut-off device required pursuant to [40 CFR §146.88(e)] and the response taken.
- The monthly volume and/or mass of the carbon dioxide stream injected over the reporting period and volume injected cumulatively over the life of the project [40 CFR §146.91(a)(5)] and LCFS Protocol Subsection C.4.3.1.2.
- Monthly annulus fluid volume added or gained [40 CFR §146.91(a)(6)].

Automatic alarm and automatic shutoff systems will be designed and installed to trigger an audible alarm in the event that pressures, flow rates, or other parameters designated by the Executive Director exceed a range or gradient specified in the injection permit per 40 CFR §146.88(e)(2). If an alarm or shutdown is triggered, the Louisiana Green Fuels, Port of Columbia Facility will immediately investigate and identify the cause of the alarm or shutoff (Please see the Emergency and Remedial Response Plan [40 CFR §146.94 (a)] for details).

4.2.1 Injection Rate, Volume, and Pressure Monitoring

Injection rates, volumes, and pressures will be set and limited to safe operating values below those specified in the authorized permit. All gauges, pressure sensing devices, and recording devices will be tested and calibrated as specified by the manufacturer. Test and calibration records will be maintained at the facility. All instruments will be housed in weatherproof enclosures, where appropriate, to limit damage from outside elements and events. The flow meters and pressure gauges will continuously record data that will be sent to a distributive control system,

Downhole flowing pressures into the reservoir will be monitored by a gauge installed near the perforations in each of the injection wells (LCFS Protocol Subsection C.4.3.1.3(a)). Gauges will be referenced to ground level at each well. Downhole pressure monitoring will protect the Injection Zone against over-injection as the carbon dioxide becomes denser. If a retrievable gauge is used, pressure gauge(s) will be periodically calibrated according to manufactures instructions and

corrected for drift. If permanent unretrievable downhole gauges are used, those gauges will be calibrated by comparison to a wireline deployed gauge run to the same depth in concert with mechanical integrity testing events. Static gradient stops will be made with the wireline deployed gauge to verify fluid column density for pressure to depth corrections. Downhole pressure gauge data will provide real-time information for verification of model predictions and Area of Review reevaluations.

4.2.2 Annulus System Monitoring

The purpose of the annulus system is to maintain a positive pressure on the tubing by casing annulus of at least 100 psi in excess of the tubing pressure. This will prevent fluid movement from the tubing out into the casing, which in turn will prevent the possible contamination of freshwater sands in the event of well casing or injection tubing failure.

Integrity of the well's annulus system is achieved by the monitoring of the annulus system at the wellhead. Annulus monitoring equipment used for each injection well includes an annulus tank, an annulus pump (small volume/high pressure), well flow meters, pressure monitoring cells, and pressure control valves. Alternate annulus construction may use a pressurized nitrogen system to maintain a constant pressure on the annulus ((LCFS Protocol Subsection C.4.3.1.3(f))). Annulus pressures will be monitored continuously. Deviations from expected changes could indicate a potential loss of mechanical integrity in the well annulus system. Observed deviations will initiate a well shutdown and investigation to determine the root cause of the observed deviation. Details are contained in the Emergency and Remedial Response Plan [40 CFR §146.94(a)] in Module E.

Annulus brine tank fluid levels (and volumes) will be monitored for indications of system losses/gains and recorded daily.

5.0 CORROSION MONITORING

Per requirements of 40 CFR §146.90(c), LAC §3625.A.3 (State of Louisiana), and LCFS Protocol Subsection C.4.1(a)(3), the Louisiana Green Fuels, Port of Columbia Facility will monitor well materials during the operational period. This will be accomplished by using corrosion coupons of well construction materials, which will be monitored for loss of mass and thickness, and will be visually inspected for evidence of cracking, pitting, and other signs of corrosion. This testing will ensure that the well components meet the minimum standards for material strength and performance. The coupon monitoring program is described in the following sections.

5.1 MONITORING LOCATION AND FREQUENCY

Coupon samples of the well construction materials (well casing, tubing and any other well parts in contact with carbon dioxide such as the packer and wellhead) will be mounted in a tray located in the common flowline to the injection wells, upstream of the flow distribution header. The tray of coupons will be in contact with the carbon dioxide stream during all injection operations. This will ensure that the tray location will provide representative exposure of the samples to the carbon dioxide composition, temperature, and pressures that will be seen at the wellhead and injection tubing. The holders and location of the system will be included in the pipeline design and will allow for continuation of injection during sample removal for testing.

The frequency of corrosion coupon collection and testing will be conducted on a quarterly basis per 40 CFR §146.90(c). Baseline measurements on all coupon samples will be made prior to initiation of injection of carbon dioxide. Commencing with the initiation of injection operations, the initial monitoring event will occur at the end of the first calendar quarter (even if less than 3 months). Subsequent monitoring will occur at the end of each calendar quarter. This equates to a schedule as follows:

1. March 31 – End of Calendar 1st Quarter
2. June 30 – End of Calendar 2nd Quarter
3. September 31 – End of Calendar 3rd Quarter
4. December 31 – End of Calendar 4th Quarter

The schedule will then repeat using this quarterly sample cycle for the lifetime of the injection operations. Coupon compositions and details will be specified as part of conveyance pipeline and final well design.

5.2 SAMPLE DESCRIPTION

The Louisiana Green Fuels, Port of Columbia Facility is proposing that a corrosion coupon (weight loss) technique will be used for monitoring purposes, as it is the best known and simplest of all corrosion monitoring techniques (the alternative is to use flow line loops). The corrosion monitoring system will be located downstream of all process compression/dehydration/pumping equipment (*i.e.*, at the beginning of the flow distribution header to the injection wells). This will allow for monitoring at a single location for each of the operating injection wells. Corrosion coupons representative of the well construction materials (Table 4) will be inspected, photographed, and weighed prior to placement into the flowline establish a baseline. Prior to installation of the corrosion monitoring system, the following information will be recorded:

1. Coupon Serial Number;
2. Installation date;
3. Identification of the location of the system; and
4. Orientation of the coupon holder.

The coupon method involves exposing a specimen sample of material (the coupon) to a process environment for a given duration, then removing the specimen for analysis. The Corrosion Monitoring Plan will be implemented following initial installation of the test coupons in the flowline, as follows:

- Consult maintenance schedule to determine when to remove test coupons from corrosion monitoring holders (coincident with end of calendar quarter);
- Remove and inspect coupons on a calendar quarterly basis and quantitatively evaluate for corrosion according to ASTM G1 – 03 (2017) or NACE Standard RP0775-2005 Item No. 21017 standards guidelines;
- Place coupons in proper receptacle for safe transport to measurement and weighing

equipment;

- Photograph each coupon as received. Visually inspect each corrosion coupon for any pitting, stress corrosion cracking or scale buildup. Analyze corrosion coupons by weighing each coupon (to nearest 0.0001 gm) and measuring length, width and height of the coupon (to nearest 0.0001 inch);
- Record information for each coupon including date of measurement, coupon identity (coupon number and metal grade) and coupon weight in grams, and include any observations of excessive weight loss or pitting, stress corrosion cracking or scale buildup;
- Determine if current corrosion coupon can be returned to the monitoring test holder, make a note of coupon return, or if not make a note of installation of a new coupon.

Table 4: List of equipment coupon with material of construction

Equipment Coupon	Material of Construction
Surface Piping	"as built" material in contact with CO_2
Wellhead	Chrome14, or "as built" trim material in contact with CO_2
Injection Tubing	Chrome14, or "as built" material in contact with CO_2
Packer	Chrome14, or "as built" trim material in contact with CO_2

Samples will be collected by trained and authorized personnel and submitted to a third-party analytical laboratory for analysis. Results of the analysis will be compared to the pre-project baseline of the coupons. Basic details regarding the laboratory analysis are explained in the attached QASP, however, specific details will be provided and updated by the selected corrosion laboratory vendor. Results will be submitted through the GSDT semi-annual reporting tool. The UIC Program Director will independently assess the results of the corrosion monitoring to assess the integrity of the injection well.

5.3 ALTERNATIVE TESTS

Per 40 CFR §146.90 and LCFS Protocol Subsection C.4.3.1.4, the Louisiana Green Fuels, Port of Columbia Facility may run a casing inspection log(s) to determine the presence or absence of corrosion in the protection (longstring) casing whenever the tubing is pulled from the well, or at the request of the UIC Program Director. Proposed casing inspection logs may include multi-finger

caliper, ultrasonic imaging, magnetic flux leakage, and electromagnetic imaging tools as they are industry standard for determining casing thickness and identifying internal and external corrosion. The log(s) will be compared to those run during the initial construction of the well (40 CFR §146.87). Additional inspection logging program may be implemented may should the coupons show undue corrosion in excess of the design-life criteria.

Alternative testing other than those listed above may be conducted, with the written approval of the UIC Director. To obtain approval for alternative testing, the Louisiana Green Fuels, Port of Columbia Facility will submit a written request to the UIC Director setting forth the proposed test and all technical data supporting its use ahead of any proposed testing.

6.0 IN ZONE (IZMI) MONITORING – TUSCALOOSA/PALUXY FORMATION

The Louisiana Green Fuels, Port of Columbia Facility will monitor pressure and temperature in the Tuscaloosa/Paluxy Injection Zone during the operation period (Figures 1 and 2).

The Tuscaloosa/Paluxy Injection Zone will be monitored at the Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well (SN 975841), located 5,273 feet southeast of the injection wells. The Injection Zone will also be monitored at several offset abandoned oil and gas wells, including:

- Bradford-Brown Trust Shipp No. 1 (SN137783) well, located approximately 10,152 feet north and up dip of the facility;
- Bass Keahey No.1 (SN165395) well, located approximately 13,730 feet northeast and up dip of the facility;
- Southern Carbon USA No. 1 (SN34225) well, located approximately 37,850 feet east- southeast of the facility; and
- Murphy Meredith No. 1 (SN23356) well, located approximately 28,150 feet east-southeast of the facility.

Each of the offset wells will be re-entered and completed as monitor wells prior to initiating the sequestration of carbon dioxide. This will allow the Port of Columbia Facility to obtain background/baseline data from the monitor wells.

6.1 TUSCALOOSA/PALUXY FORMATION – DIRECT MONITORING

The Port of Columbia Facility will perform direct monitoring of the advancing carbon dioxide plume with the five in-zone monitor wells:

1) Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well (SN975841), located 5,273 feet southeast and down dip of the injection wells, and

2) Bradford-Brown Trust Shipp No. 1 (SN137783) well, located approximately 10,152 feet north and up dip of the facility;

3) Bass Keahey No.1 (SN165395) well, located approximately 13,730 feet northeast and up dip of the facility;
4) Southern Carbon USA No. 1 (SN34225) well, located approximately 37,850 feet east-southeast of the facility; and
5) Murphy Meredith No. 1 (SN23356) well, located approximately 28,150 feet east-southeast of the facility.

The locations of these monitor wells will constrain the maximum plume dimensions until the advancing carbon dioxide plume intersects a well.

6.1.1 Monitoring Location and Frequency

Direct monitoring will be conducted at the Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well, located 5,273 feet southeast and down dip of the facility, and at four offset abandoned oil and gas wells (Figure 2). Table 5 shows the planned monitoring methods, locations, and frequencies for formation water quality and geochemical monitoring within the Tuscaloosa/Paluxy Injection Zone.

Modeling shows that pressure is a more robust and diagnostic detection method in deep confined saline aquifers. Under typical flow gradients in saline formations, the carbon dioxide pressure "front" is unlikely to propagate farther from the injection point than the sequestered carbon dioxide (see Module B). The Louisiana Green Fuels, Port of Columbia Facility will instead measure and continuously record bottomhole pressure/temperature in the two proposed "in zone" monitoring wells ((LCFS Subsection C.4.3.2.1(d)). Pressure/temperature monitoring will be used as a trigger to initiate fluid sampling as the sequestered carbon dioxide approaches a monitor well.

Table 5: Monitoring in the Tuscaloosa/Paluxy Injection Zone.

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Tuscaloosa/Paluxy	Downhole pressure monitoring	Injection Wells	Well Field	Real time daily read out.
Tuscaloosa/Paluxy	Pulsed Neutron Logging	Injection Wells	Well Field	Baseline log at prior to project start.

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
	Pulsed Neutron Logging	Injection Wells	Well Field	Repeat Surveys if anomaly is observed
Tuscaloosa/Paluxy	Downhole pressure monitoring	2 offset Monitoring Wells	Over area of review	Real time daily read out.
Tuscaloosa/Paluxy	Pulsed Neutron Logging	2 offset Monitoring Wells	Over area of review	Baseline log at prior to project start.
	Pulsed Neutron Logging	2 offset Monitoring Wells	Over area of review	Repeat Surveys if anomaly is observed, adaptive thereafter
Tuscaloosa/Paluxy	Baseline geochemical sampling	2 offset Monitoring Wells	Over area of review	Baseline Sample at prior to project start.
	Follow-up Geochemical testing if signal is observed	2 offset Monitoring Wells	Over area of review	Repeat sampling if anomaly is observed
Tuscaloosa/Paluxy	Repeat seismic method designed for plume tracking, also detect any fluid above interval	Injection Wells and potentially at Monitor Wells	Azimuthal coverage of the plumes	Baseline, 1 year, 3 years, 5 years, and then every 5 years thereafter

The goal of monitoring in the Tuscaloosa/Paluxy Injection Zone is to constrain the geometry and ascertain the size of the advancing carbon dioxide plume. These monitor points provide site-specific and immediate data on the presence of carbon dioxide in the subsurface. An initial baseline geochemical analysis of the formation fluids will be performed prior to injection operations at the facility LCFS Protocol Subsection C.2.3(a)(9)(A).

If an increase in pressure is detected in the monitoring well pressure gauge(s), this will trigger conditional, adaptive geochemical sampling of the formation fluids as this increase in pressure is expected to attributable to the imminent arrival of the sequestered carbon dioxide plume. The collected samples will be sealed, dated, and sent to an authorized third-party laboratory for analysis. Sampling will only occur if pressure changes are detected, either downhole or at the wellhead. The frequency of geochemical sampling will be conducted on an “as needed” basis if the pressure signal triggers additional testing.

6.1.2 Analytical Procedures

An initial baseline fluid sample will be collected from the Tuscaloosa/Paluxy Injection Zone during completion and well development activities in the monitor wells prior to injection operations. These fluid samples will provide the baseline measurements for formation fluids and document any spatial variability. Table 6 identifies the parameters to be monitored and the analytical methods the Louisiana Green Fuels, Port of Columbia Facility will use.

Table 6: Summary of analytical and field parameters for ground water samples – Tuscaloosa/Paluxy Injection Zone

Parameters	Analytical Methods
Dissolved CO_2 gas by headspace	Gas Chromatography (GC)
Dissolved CH_4 gas by headspace	Gas Chromatography (GC)
Hydrocarbons	Gas Chromatography (GC)
Dissolved inorganic carbon	Combustion
Bicarbonate	Titration
$\delta D\ CH_{24}$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$\delta C^{13}\ CO_2$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$\delta C^{13}\ CH_4$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$C^{14}\ CO_2$	Accelerated mass spectrometry (AMS).
C^{14} Methane	Accelerated mass spectrometry (AMS).
Isotopic composition of selected major or minor constituents (*e.g.*, Sr $^{87/86,}$ S)	Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS)
Cations: Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Pb, Sb, Se, Si, Ti, Zn,	ICP-MS or ICP-OES, ASTM D5673, EPA 200.8 Ion Chromatography, EPA Method 200.8, ASTM 6919
Anions: Br, Cl, F, NO_3, SO_4,	Ion Chromatography, EPA Method 300.8, ASTM 4327
Total Dissolved Solids	EPA 160.1, ASTMN D5907-10
Alkalinity	EPA 310.1
pH (field)	EPA Method 150.1
Specific Conductance (field)	EPA 120.1, ASTM 1125
Temperature (field)	Thermocouple
Hardness	ASTM D1126
Turbidity	EPA 180.1

Parameters	Analytical Methods
Specific Gravity	Modified ASTM 4052
Density	Modified ASTM 4052

The initial parameters identified in Table 6 may be revised and include additional components for testing dependent on the initial geochemical evaluation. The fluid samples will be sent to a third-party laboratory accredited by the Louisiana Department of Environmental Quality for analysis.

6.1.3 Sampling Methods

The sampling system used to sample and quantify free and dissolved gases and the aqueous phases in equilibrium with these gasses will be supplied by a third-party vendor (Schlumberger, Expro, or equivalent vendor using downhole PVT sampler or equivalent tool). Note that most deep sampling is designed for hydrocarbons; this testing should focus on all gasses and formation fluids]. Downhole samples are preferred; however, surface samples may be collected for expediency.

The following sampling protocol would be: purge the casing volume to bring fresh fluids that have not reacted with casing and tubing to the sample point within the wellbore. Deploy commercial downhole sampler on slickline to collect a fluid sample at pressure and then close to retain gas phases as sample is transported to the surface. Conserve gas volumes as samples are stepped to atmospheric pressure for shipping and analysis. Filter and conserve samples following protocols for brine sampling. All sample containers will be labeled with durable labels and indelible markings. A unique sample identification number and sampling date will be recorded on the sample containers. The sample container will be sealed and sent to an authorized third-party laboratory.

Repeat sampling and frequency (adaptive program) to be determined based on results.

6.1.4 Analysis Procedures and Chain of Custody

Samples will be analyzed by a third party laboratory accredited by the Louisiana Department of Environmental Quality (https://internet.deq.louisiana.gov/portal/divisions/lelap/accredited-laboratories) using standardized procedures for gas, major, minor and trace element compositions.

Detection limits will be dependent on equipment used for the analytical methods by the selected qualified vendor and meet the minimum levels set forth in the QASP.

The sample chain-of-custody procedures will be dependent on vendor selection as the vendor will assume the custody of the samples. These procedures will document and track the sample transfer to laboratory, to the analyst, to testing, to storage, to disposal (at a minimum). A sample chain of custody procedures is illustrated in Appendix 1. If significant differences in geochemistry between the two monitor wells is observed, each well may be resampled to ensure validity of the baseline analyses.

The initial parameters identified in Table 6 may be revised and include additional components for testing dependent on the initial geochemical evaluation.

6.2 TUSCALOOSA/PALUXY FORMATION – INDIRECT MONITORING

Indirect plume monitoring will be employed in the injection wells and the "in zone" monitoring wells to define the location, extent, and thickness of the injected carbon dioxide (LCFS Subsection C.4.3.2.1). Pulsed neutron capture logs will be used to monitor carbon dioxide saturation at the injection wells (qualitative flow distribution) and in the two Tuscaloosa/Paluxy Injection Zone Monitoring Wells once carbon dioxide is detected. Saturation logging within the two Tuscaloosa/Paluxy Injection Zone Monitoring Wells will help in understanding the flow distribution away from the Port of Columbia Facility.

The areal distribution of the carbon dioxide plume in the Tuscaloosa/Paluxy Injection Zone will be determined using time-lapse seismic techniques (LCFS Subsection C.4.3.2.1(c)). The displacement of brine by injected carbon dioxide within sandstones, such as the those of the Tuscaloosa/Paluxy Formation, at similar project depths is well documented to produce a strong negative change in acoustic impedance Vasco et al., 2019). This change in impedance can be detected by many time-lapse seismic methods. Leading-edge techniques for time-lapse imaging of carbon dioxide plumes include time-lapse vertical seismic profiling (Daley and Korneev, 2006; Gupta, et al., 2020), azimuthal vertical seismic profiling (Gordon, et al., 2016), sparse array walk-away surveys or scalable, automated, semipermanent seismic array "SASSA" (Roach, et al., 2015; Burnison, et al., 2016; Livers, 2017; Adams, et al., 2020). These techniques are expected to be

robust in monitoring plume growth and less invasive from a surface footprint. At a minimum, the array of acoustic source sites will be oriented along the maximum and minimum orientations of the modeled plume and will be adjusted following each survey results. Frequency will be dependent on the monitoring method chosen. For time-lapse profiling and sparse array walk-away techniques, intervals will be 1 year, 3 years, 5 years, and then every 5 years thereafter. For SASSA episodic data from the array can be obtained using an adaptive monitoring strategy (Burnison, et al., 2016; Livers, 2017; Adams, et al., 2020).

For the vertical seismic profile array type monitoring, distributed acoustic sensing (DAS) fiber may be installed on the injection wells. These fiber cables will be contained within the cement behind the long string casing, sending signal to a surface interrogator to detect acoustic signal. Signals will be produced by radial distribution of well-coupled cement filled pad locations (*e.g.*, a permanent, excavated pit filled with cement). Sources will either be permanently bolted units or intermittently attached during monitoring data collection events. The following considerations will lead to selection of the specific method for plume tracking:

1) Cost-effective and low environmental-footprint monitoring methods are favored over more expensive, larger environmental-footprint methods.
2) Methods with quicker turnaround time to deliver results from data collection to processing are favored over methods that require more robust acquisition and processing, and thus a much longer turnaround time.
3) Anticipated radial geometry and extent of the injected CO_2 plume with time.
4) The presence of of wetlands (if any) in the area may preclude the use of numerous source locations on grounds of poor access and the risk of excessive environmental damage during data acquisition. Temporal changes in surface culture could affect surface source distribution, damaging repeatability.
5) Permanent installations for acoustic sources optimize repeatability, which is critical in time-lapse tracking.
6) The availability and demonstrated effectiveness of DAS fiber as an acoustic receiver favors this type of installation.
7) The same arrays will be used into the PISC period.

Vendors will be contracted to design the area and processing flow, install DAS fiber, supply interrogators(s) for both temperature and acoustic signals, design the source arrays including frequency and coupling to assure good signal-to-noise to detect impedance contrast at depth and thickness modeled, and data analysis. Report from azimuthal VSPs will be used to track carbon dioxide migration along selected azimuths. These measurements can be plotted against equivalent model outputs and be used to validate or correct as needed the fluid flow model and plume tracking predictions to satisfy the requirements at 40 CFR §146.90(g).

In addition, the use of DAS fiber, if deployed, will allow very wide aperture of the acoustic array and will include surveillance of strata above the sequestered carbon dioxide plume. This will provide further assurance that no out-of-zone migration is occurring within the monitored area.

7.0 ABOVE ZONE (AZMI) MONITORING – ANNONA SAND

The Louisiana Green Fuels, Port of Columbia Facility will monitor pressure and temperature in the Annona Sand, located above the Tuscaloosa/Paluxy Injection Zone during the operation period. This will allow for early detection of any out-of-zone movement of either carbon dioxide or intraformational fluids above the Tuscaloosa/Paluxy Injection Zone. The Annona Sand is a blanket sand within the area of the injected carbon dioxide plume and the Area of Review. Monitoring the Annona Sand will allow for the monitoring of pressure over a large area. As shown in the injection/falloff test conducted in the Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well, the Annona Sand has relatively high permeability (56 millidarcies) that will facilitate the transmission of a pressure signal should formation fluids or carbon dioxide start to flow into it.

The Annona Sand will be monitored at both the Whitetail Operating, LLC, Louisiana Green Fuels #1 (SN975841) stratigraphic test well, located 5,273 feet southeast and down dip of the facility, and at the Bradford-Brown Trust Shipp No. 1 (SN20131) well, located approximately 10,152 feet northwest and up dip of the injection wells (Figures 1 and 2). Both locations will be engineered for continuous IZMI and AZMI Monitoring.

In the Annona AZMI Monitoring zone, each well will be fitted with real-time, continuously recording downhole pressure/temperature gauges. Gauges will be referenced to ground level at each well. Alternately, a “light” fluid column to allow monitoring and recording pressures at surface may be used. Native formation water, per LCFS Protocol Subsection C.2.3(a)(9)(B), will be sampled initially upon well construction (including for dissolved and free gases) for baseline characterization purposes (Annona fluids sampling and analyses have been completed in the Whitetail Operating, LLC, Louisiana Green Fuels #1). A native formation water will be sampled initially (including for dissolved and free gases) for baseline characterization purposes in the repurposed Bradford-Brown Trust Shipp No. 1 (SN20131) well when it is re-entered for conversion to a monitor well.

Changes in water composition are not expected in the Annona AZMI Monitoring Zone. However, these AZMI Zone Monitor wells will provide direct measurement, when or if, the sequestered

carbon dioxide plume ever reaches the Annona Sand monitored at either well location. Should the presence of carbon dioxide be detected in either well (either by change in downhole pressure and temperature or by surface pressure and temperature changes), a direct fluid sampling program will be triggered and initiated in each well. Work will be conducted by a qualified vendor and the selected analytical laboratory will be compliant with the Louisiana Environmental Laboratory Accreditation Program.

7.1 AZMI MONITORING ABOVE TUSCALOOSA/PALUXY INJECTION ZONE – ANONNA SAND

AZMI monitoring in the Annona Sand will provide early detection of carbon dioxide and/or inter-formational fluid flow within the Storage Complex. As such, AZMI monitoring will provide an early warning before fluids may be able to migrate up to the base of the Midway Shale Confining Zone. Monitoring in the Annona Sand will also allow for direct monitoring should the interval be used as an Injection Zone at the Port of Columbia Facility. Should the Annona Sand be used to sequester carbon dioxide at the Port of Columbia Facility, these wells will become In-zone monitor wells (IZMI wells).

7.1.1 Monitoring Location and Frequency

The Annona Sand will be monitored at both the Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well (SN975841), located 5,273 feet southeast and down dip of the injection wells, and at the Bradford-Brown Trust Shipp No. 1 (SN20131) well, located approximately 10,152 feet northwest and up dip of the injection wells (see Figure 2). Table 7 shows the planned monitoring methods, locations, and frequencies for pressure and temperature monitoring in the Annona Sand AZMI interval.

Modeling shows that pressure is a more robust and more diagnostic leakage detection method in deep confined saline aquifers as changes can be observed over a larger geographic area. Under typical low flow gradients in saline formations, carbon dioxide is unlikely to propagate far from the leakage point, therefore, being chemically undetectable over the larger scale. Leakage of brine from one formation to another is also unlikely to be chemically diagnostic (such as from the Tuscaloosa/Paluxy Formation up into the Annona Sand, due to similarity of native formation brine compositions in the two formations), and if ambient methane or carbon dioxide is present in the

system (such as beneath the Port of Columbia Facility), presence of carbon dioxide may not be sufficiently diagnostic either. It is anticipated that a large volume of Tuscaloosa/Paluxy formation fluid would have to infiltrate into the Annona Sand in order for it to provide a meaningful signal. Therefore, pressure monitoring should be more diagnostic.

The Louisiana Green Fuels, Port of Columbia Facility is proposing to continuously measure and record bottomhole pressure/temperature in the AZMI monitoring wells. Pressure trends potentially indicative of leakage into the Annona Sand will be readily detected using such methods. If trends indicate of potential leakage has been detected, follow-up logging (pulsed neutron logging or PVT bottomhole fluid sampling) or geochemical measurements will be conducted to assess the validity of the change in signal. Logging operations may include pulsed neutron logging in the injection wells to determine if they constitute a possible leak path.

The pressure response will be measured by a pressure/temperature gauge that will be capable of transmitting real-time, continuous pressure/temperature from the remote monitoring locations to the distributive control system at the facility. Gauges will be referenced to ground level at each well.

Table 7: AZMI Monitoring above the Tuscaloosa/Paluxy Injection Zone – Annona Sand.

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Annona	Downhole pressure monitoring	2 offset Monitoring Wells	Over area of review	Real time daily read out.
Annona	Pulsed Neutron Logging	2 offset Monitoring Wells	Over area of review	Baseline log at prior to project start.
	Pulsed Neutron Logging	2 offset Monitoring Wells	Over area of review	Repeat Surveys if anomaly is observed
Annona	Baseline geochemical sampling	2 offset Monitoring Wells	Over area of review	Baseline Sample at prior to project start.
	Follow-up Geochemical testing if signal is observed	2 offset Monitoring Wells	Over area of review	Only if anomaly is observed
Annona	Pulsed Neutron Logging	Injection Wells	Well Field	Baseline log at prior to project start.

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
	Pulsed Neutron Logging	Injecting Wells	Well Field	Repeat Surveys during MIT, adaptive if anomaly detected
Annona	Repeat seismic method designed for plume tracking, also detect any fluid in Annona	Injection Wells and potentially at Monitor Wells	Azimuthal coverage of the plumes	Baseline, 1 year, 3 years, 5 years, and then every 5 years thereafter

The goal of monitoring directly above the Tuscaloosa/Paluxy Injection Zone is to detect either brine or carbon dioxide leakage above the Injection Zone, should it occur. This provides site-specific and immediate data into the potential of a barrier breach and leakage above the Tuscaloosa/Paluxy. An initial geochemical description of the fluids will be evaluated prior to injection operations for this interval. However, pressure changes will be the initial parameter to be observed.

7.1.2 Analytical Procedures

An initial formation fluid sample will be collected from the monitoring wells prior to injection operations per LCFS Protocol Subsection C.2.3(a)(9)(B). This initial sample has been obtained from the White Tail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well. A baseline sample will also be obtained from the converted oil and gas wells during reentry and recompletion activities.

These fluid samples will provide the baseline measurements for the Annona Sand and document any spatial variability. If significant differences in geochemistry between the two monitor wells is observed, one or both wells may be redeveloped and resampled to ensure validity of the baseline analyses.

Table 8 identifies the parameters to be monitored and the analytical methods the that will be used by Louisiana Green Fuels, Port of Columbia Facility.

Table 8: Summary of analytical and field parameters for Annona Formation Fluid Samples (AZMI Monitoring Wells)

Parameters	Analytical Methods
Annona Formation	
Dissolved CO_2 gas by headspace	Gas Chromatography (GC)
Dissolved CH_4 gas by headspace	Gas Chromatography (GC)
Hydrocarbons	Gas Chromatography (GC)
Dissolved inorganic carbon	Combustion
Bicarbonate	Titration
$\delta D\ CH_{24}$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$\delta C^{13}\ CO_2$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$\delta C^{13}\ CH_4$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$C^{14}\ CO_2$	Accelerated mass spectrometry (AMS).
C^{14} Methane	Accelerated mass spectrometry (AMS).
Isotopic composition of selected major or minor constituents (*e.g.*, Sr $^{87/86,}$ S)	Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS)
Cations: Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Pb, Sb, Se, Si, Ti, Zn,	ICP-MS or ICP-OES, ASTM D5673, EPA 200.8 Ion Chromatography, EPA Method 200.8, ASTM 6919
Anions: Br, Cl, F, NO_3, SO_4,	Ion Chromatography, EPA Method 300.8, ASTM 4327
Total Dissolved Solids	EPA 160.1, ASTMN D5907-10
Alkalinity	EPA 310.1
pH (field)	EPA Method 150.1
Specific Conductance (field)	EPA 120.1, ASTM 1125
Temperature (field)	Thermocouple
Hardness	ASTM D1126
Turbidity	EPA 180.1
Specific Gravity	Modified ASTM 4052
Density	Modified ASTM 4052

The initial parameters identified in Table 8 may be revised and include additional components for testing dependent on the initial geochemical evaluation. If fluid samples are collected, then those samples will be sent to a third-party laboratory accredited by the Louisiana Department of Environmental Quality for analysis.

7.1.3 Sampling Methods

The sampling system used to sample and quantify free and dissolved gases and the aqueous phases in equilibrium with these gasses will be supplied by a third-party vendor (Schlumberger, Expro, or equivalent vendor using downhole PVT sampler or equivalent tool). Note that most deep sampling is designed for hydrocarbons; this testing should focus on all gasses and formation fluids.

The protocol for sampling shall be as follows: purge the casing volume to bring fresh fluids that have not reacted with casing and tubing to the sample point within the wellbore. Deploy a commercial downhole sampler on slickline to collect a fluid sample at pressure and then close to retain gas phases as the sample is transported to the surface. Conserve gas volumes as samples are stepped to atmospheric pressure for shipping and analysis. Filter and conserve samples following protocols for brine sampling. All sample containers will be labeled with durable labels and indelible markings. A unique sample identification number and sampling date will be recorded on the sample containers. The sample container will be sealed and sent to an authorized third-party laboratory.

Repeat sampling and frequency to be determined based on results.

7.1.4 Analysis Procedures and Chain of Custody

Samples will be analyzed by a third party laboratory accredited by the Louisiana Department of Environmental Quality (https://internet.deq.louisiana.gov/portal/divisions/lelap/accredited-laboratories) using standardized procedures for gas, major, minor and trace element compositions. Detection limits will be dependent on equipment used for the analytical methods by the selected qualified vendor and meet the minimum levels set forth in the QASP.

The sample chain-of-custody procedures will be dependent on vendor selection as the vendor will assume the custody of the samples. The procedures will document and track the sample transfer to laboratory, to the analyst, to testing, to storage, to disposal (at a minimum). A sample chain of custody procedures is contained in Appendix 1.

8.0 ABOVE CONFINING ZONE (ACZMI) MONITORING - WILCOX FORMATION

The Louisiana Green Fuels, Port of Columbia Facility will monitor pressure and temperature in a sandstone developed within the basal Wilcox Formation, immediately above the Midway Shale Confining Zone. This will allow for early detection of any out-of-zone movement of either carbon dioxide or intraformational fluids above the Midway Shale Confining Zone and out of the sequestration complex (LCFS Protocol Subsection C.4.1(a)(10)). The basal Wilcox sandstone is generally a blanket sand within the area of the injected carbon dioxide plume and the Area of Review. The Wilcox will be monitored in a dedicated ACZMI Monitor Well Installed at the Port of Columbia Facility The well will be engineered for continuous monitoring and set up for fluid sampling on a quarterly basis.

In the Wilcox ACZMI Monitoring zone, the well will be fitted with a real-time, continuously recording downhole pressure/temperature gauge (LCFS Protocol Subsection C.4.1(a)(4)). The gauge will be referenced to ground level. Alternately, a “light” fluid column to allow monitoring and recording pressures at surface may be used. Native formation water from the Wilcox will be sampled initially upon well construction (including a quantification of both dissolved and free native gases) for baseline characterization purposes (LCFS Protocol Subsection C.2.3(a)(9)(B)).

Changes in water composition are not expected in the basal Wilcox ACZMI Monitoring zone. However, the ACZMI Zone Monitor well will provide direct measurement, when or if, the sequestered carbon dioxide or deeper formation brines ever rise up to the base of the Wilcox Formation. Baseline and quarterly fluid sampling will be conducted in the ACZMI well. If practical to do so, baseline sampling will be performed for at least one year prior to initiation of sequestration injection per LCFS Protocol Subsection C.2.5(b)(c)(d)(e). Should the well begin to exhibit the presence of carbon dioxide (either by change in downhole pressure and temperature or by surface pressure and temperature changes or a change in water quality), an adaptive fluid sampling program will be initiated with more frequent monitoring events. Field sampling work will be conducted by a qualified vendor and the selected analytical laboratory will be compliant with the Louisiana Environmental Laboratory Accreditation Program.

8.1 ACZMI MONITORING – WILCOX FORMATION

Per Standard 40 CFR §146.90(d), geochemical and water quality will be monitored within the sandstone of the basal Wilcox Formation. At the Port of Columbia Facility, the Wilcox Formation directly overlies the Midway Shale Confining Zone and is comprised of alternating saline sands and thin shale beds. In Caldwell Parish, the upper portion of the Wilcox Formation, including several sandstones ranging from 1,350 feet to 2,200 feet below ground level, has been used by local oil and gas operators for the disposal of produced saltwater in wells completed as saltwater disposal (SWD) wells. Eight SWD wells have been drilled within four miles of the proposed Port of Columbia Facility. Of these eight wells, six are currently plugged and abandoned, and the remaining two remain active. The two active SWD wells are injecting produced brine into the upper Wilcox sandstones at depths ranging from 1,368 to 2,200 feet below ground level. Strategic Biofuels will annually monitor the SONRIS website for any new Class II injection wells or any status changes in the existing SWD wells within a four-mile radius of the facility.

8.1.1 Monitoring Location and Frequency

Figure 2 and Table 9 shows the planned monitoring methods, locations, and frequencies for direct and indirect monitoring of ground water quality and geochemistry above the Midway Shale Confining Zone. A porous Lower Wilcox sandstone located at a depth of 2,846 to 2,866 feet below ground level (as stratigraphically referenced to the Southwestern Energy Production Company CPC #1 well (SN 235656), located near the southeastern corner of the facility property) that is positioned stratigraphically just above the top of the Midway Shale will be the targeted monitoring interval. The Lower Wilcox sandstone reservoir monitored in the ACZMI well will be at a depth that will be below the formerly productive Reynolds Coal Seam (lignite) of the Lower Wilcox Formation, as previously produced in the overlying (now mostly abandoned) Riverton CBM Gas Field. Strategically, the ACZMI Monitoring well is located near the point of carbon dioxide injection, where the elevated formation pressure in the Tuscaloosa/Paluxy would be the greatest.

Modeling shows that pressure monitoring is a more robust and more diagnostic leakage detection method in deep confined saline aquifers. Under typical low flow gradients in saline formations, a carbon dioxide pressure signal is unlikely to propagate far from the leakage point and would be chemically undetectable. Leakage of brine from one formation to another is also unlikely to be

chemically diagnostic, and if ambient methane or carbon dioxide is present in the system, carbon dioxide may not be chemically diagnostic either. The Louisiana Green Fuels, Port of Columbia Facility will instead measure bottom hole pressure in the onsite ACZMI monitoring well, which will be continuously monitored. If leakage trends are detected, follow-up testing, logging, or geochemical measurements will be conducted to assess the change in signal (adaptive monitoring).

Strategic Biofuels will also monitor ground water quality and geochemical changes in the basal Wilcox Formation above the Midway Confining Zone during the operational and post-operational periods to meet the requirements of 40 CFR §146.90(d). Groundwater sampling methods to be employed, including sampling standard operating procedures as adapted from Striggow (2017) or as approved by the Director. Sample containers will be new and of an appropriate material and size for the analyte. Sufficient volumes will be collected to complete all of the specified analyses in Table 10. Appropriate preservation of each sample container will be completed upon sample collection (see QASP). Chain-of-custody will be documented using a standardized form from the analytical laboratory and will be retained and archived to allow tracking of sample status. This will include any required duplicates collected and appropriate field and trip blanks included for quality assurance. Completing the field chain-of-custody form will be the responsibility of groundwater sampling personnel.

The frequency of groundwater quality sampling will be conducted on a quarterly basis. A baseline series of sampled groundwater quality will be established over a period of a year or more ahead of the initiation of carbon dioxide sequestration (per LCFS Protocol Subsection C.2.5(b)(c)(d)(e)). Then, commencing with the initiation of carbon dioxide injection operations, the initial monitoring event will occur at the end of the first calendar quarter (even if less than 3 months). Subsequent monitoring will occur at the end of each calendar quarter. This equates to a schedule as follows:

1. March 31 – End of Calendar 1st Quarter
2. June 30 – End of Calendar 2nd Quarter
3. September 31 – End of Calendar 3rd Quarter
4. December 31 – End of Calendar 4th Quarter

The schedule will then repeat using this quarterly sample cycle for the duration of injection

operations.

Table 9: ACZMI Monitoring above the Midway Confining Zone – Wilcox Formation.

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Lower Wilcox	Downhole pressure monitoring	Onsite deep Wilcox Monitoring Well	Over area of review	Real time daily read out.
Lower Wilcox	Pulsed Neutron Logging	2 offset Monitoring Wells	Over area of review	Baseline log at prior to project start.
	Pulsed Neutron Logging	2 offset Monitoring Wells	Over area of review	Repeat Surveys if anomaly is observed
Lower Wilcox	Baseline geochemical sampling	2 offset Monitoring Wells	Over area of review	Baseline Sample at prior to project start.
	Follow-up Geochemical testing if signal is observed	2 offset Monitoring Wells	Over area of review	Only if anomaly is observed
Lower Wilcox	Fluid Sampling	Onsite deep Wilcox Monitoring Well	Area of highest pressure buildup	Baseline: Initial and quarterly 1 year ahead of injection Year 0 to 5 – Quarterly Year 5 to End – Annually

The goal of monitoring directly above the Midway Shale Confining Zone is to detect the leakage or upward movement of either formation brine or carbon dioxide from the Sequestration Complex, should it occur. An initial geochemical description of the fluids will be evaluated prior to injection operations for this interval.

The pressure response measured will be measured by an onsite (within the facility boundary) ACZMI monitoring well, dedicated with the sole purpose of monitoring just above the Midway Shale Confining Zone. Pressure monitoring in the above confining zone well will be isolated within the sandstones of the Lower Wilcox formation, below the formerly productive Reynolds Coal Seam (lignite) of the Lower Wilcox Formation, as previously produced in the overlying (now mostly abandoned) Riverton CBM Gas Field. One or more transmissive basal Wilcox sandstones may be identified as the optimal monitoring interval. Higher sensitivity to leakage is obtained by

selecting sandstones that have larger areal continuity but are stratigraphically thinner. The well will be completed with a downhole pressure/temperature gauge run on tubing or hung on wireline. The pressure gauge will provide a readout of real-time, continuous pressures and will be referenced to ground level.

If a pressure anomaly is detected by the downhole pressure gauge installed in the monitoring well, the anomaly will be evaluated. If it is determined that the anomaly appears to be real following the evaluation, this will trigger increased conditional, adaptive geochemical sampling of the formation fluids. Samples will be collected from the basal Wilcox sandstone or sandstones in the onsite monitoring well. The collected samples will be sealed, dated, and sent to an authorized third-party laboratory for analysis. The frequency of enhanced geochemical sampling will be conducted on an "as needed" basis if the pressure signal triggers additional testing.

If pressure and sample analysis confirms potential leakage into the strata overlying the Confining Zone, then injection operations will cease and will trigger the procedures set out in the "*Emergency Remedial and Response Plan*". Sampling of the near-surface ground waters and soil-gas sampling will be initiated to define the impact and reach of the potential leakage above the Midway Shale Confining Zone.

8.1.2 Analytical Procedures

An initial formation fluid sample will be collected from the basal Wilcox ACZMI Monitoring Well prior to injection operations. The initial fluid sample will provide the baseline measurements for the Wilcox Formation per LCFS Protocol Subsection C.2.3(a)(9)(B).

Table 10 identifies the parameters to be monitored and the analytical methods the Louisiana Green Fuels, Port of Columbia Facility will use.

Table 10: Summary of analytical and field parameters for Wilcox Formation Fluid Sample (ACZMI Monitoring Well)

Parameters	Analytical Methods
Dissolved CO_2 gas by headspace	Gas Chromatography (GC)
Dissolved CH_4 gas by headspace	Gas Chromatography (GC)
Hydrocarbons	Gas Chromatography (GC)

Parameters	Analytical Methods
Dissolved inorganic carbon	Combustion
Bicarbonate	Titration
δD CH_{24}	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
δC^{13} CO_2	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
δC^{13} CH_4	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
C^{14} CO_2	Accelerated mass spectrometry (AMS).
C^{14} Methane	Accelerated mass spectrometry (AMS).
Isotopic composition of selected major or minor constituents (*e.g.*, Sr $^{87/86,}$ S)	Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS)
Cations: Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Pb, Sb, Se, Si, Ti, Zn,	ICP-MS or ICP-OES, ASTM D5673, EPA 200.8 Ion Chromatography, EPA Method 200.8, ASTM 6919
Anions: Br, Cl, F, NO_3, SO_4,	Ion Chromatography, EPA Method 300.8, ASTM 4327
Total Dissolved Solids	EPA 160.1, ASTMN D5907-10
Alkalinity	EPA 310.1
pH (field)	EPA Method 150.1
Specific Conductance (field)	EPA 120.1, ASTM 1125
Temperature (field)	Thermocouple
Hardness	ASTM D1126
Turbidity	EPA 180.1
Specific Gravity	Modified ASTM 4052
Density	Modified ASTM 4052

The initial parameters identified in Table 10 may be revised and include additional components for testing dependent on the initial geochemical evaluation. If the fluid samples are collected, then they will be collected and sent to a third-party laboratory accredited by the Louisiana Department of Environmental Quality for analysis.

8.1.3 Sampling Methods

The sampling system used to sample and quantify free and dissolved gases and the aqueous phases in equilibrium with those gasses will be supplied by a third-party vendor (Schlumberger, Expro, or equivalent vendor using downhole PVT sampler or equivalent tool). Bottom hole samples are

preferred; however, surface samples may be used for expediency.

The protocol for sampling shall be as follows: purge the casing volume to bring fresh fluids that have not reacted with casing and tubing to the sample point within the wellbore. Deploy commercial downhole sampler on slickline to collect a fluid sample at pressure and then close to retain gas phases as sample is transported to the surface. Conserve gas volumes as samples are stepped to atmospheric pressure for shipping and analysis. Filter and conserve samples following protocols for brine sampling. All sample containers will be labeled with durable labels and indelible markings. A unique sample identification number and sampling date will be recorded on the sample containers. The sample container will be sealed and sent to an authorized third-party laboratory.

Repeat sampling and frequency to be determined based on results.

8.1.4 Analysis Procedures and Chain of Custody

Samples will be analyzed by a third party laboratory accredited by the Louisiana Department of Environmental Quality (https://internet.deq.louisiana.gov/portal/divisions/lelap/accredited-laboratories) using standardized procedures for gas, major, minor and trace element compositions. Detection limits will be dependent on equipment used for the analytical methods by the selected qualified vendor and meet the minimum levels set forth in the QASP.

The sample chain-of-custody procedures will be dependent on vendor selection as they will assume the custody of the samples. The procedures will document and track the sample transfer to laboratory, to the analyst, to testing, to storage, to disposal (at a minimum). A sample chain-of-custody procedure is illustrated in Appendix 1.

8.2 USDW MONITORING – PUBLIC WATER SUPPLY WELLS

Public water supply in the area is supplied by the East Columbia Water District. The Louisiana Department of Health routinely monitors for constituents in the drinking water according to Federal and State laws. The Port of Columbia Facility will secure split samples from the municipal water wells when they are sampled by the East Columbia Water District. These samples will be used to establish the baseline ground water quality and will be monitored for any indicated long-

term changes in measured parameters.

8.2.1 Monitoring Location and Frequency

The Louisiana Green Fuels, Port of Columbia Facility is working with the East Columbia Water District (ECWD), located in Riverton, Louisiana (1 mile south from the facility location). Two Cockfield Aquifer water supply wells will be used for geochemical testing for USDW's. Table 11 shows the planned monitoring methods, locations, and frequencies for ground water quality and geochemical monitoring of the Cockfield Aquifer.

Table 11: Monitoring of ground water quality and geochemical parameters in a USDW – Public Water Supply Wells

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Cockfield Formation	Baseline geochemical sampling	Municipal Wells in Riverton	Over area of review	One Year prior to project start and sample at start.
Cockfield Formation	Follow-up Geochemical testing	Municipal Wells in Riverton	Over area of review	Quarterly during Injection Operations Annually during post-injection site closure phase.

The frequency of groundwater quality sampling will be conducted on a quarterly basis. A baseline will be established over a period of a year or more ahead of initiation of sequestration (per LCFS Protocol Subsection C.2.5(b)(c)(d)(e)). Commencing with the initiation of injection operations, the initial monitoring even will occur at the end of the first calendar quarter (even if less than 3 months). Subsequent monitoring will occur at the end of each calendar quarter. This equates to a schedule as follows:

5. March 31 – End of Calendar 1st Quarter
6. June 30 – End of Calendar 2nd Quarter
7. September 31 – End of Calendar 3rd Quarter
8. December 31 – End of Calendar 4th Quarter

The schedule will then repeat using this quarterly sample cycle for the duration of injection

operations.

For Post-Closure sampling, the frequency of sampling will continue to be performed on a quarterly basis for the first year after closure. Then from second year on, the samples will be collected and tested on an annual basis, within 45 days of the prior sample anniversary, for a determined post-site care closure timeframe.

8.2.2 Analytical Procedures

Table 12 identifies the parameters to be monitored and the analytical methods the Louisiana Green Fuels, Port of Columbia Facility will use for samples from Public Water Supply wells.

Table 12: Summary of analytical and field parameters for ground water samples – Public Water Supply Wells

Parameters	Analytical Methods
Cockfield Formation	
Total Dissolved Solids	EPA 160.1, ASTMN D5907-10
Alkalinity	EPA 310.1
pH (field)	EPA Method 150.1
Specific Conductance (field)	EPA 120.1, ASTM 1125
Temperature (field)	Thermocouple
Hardness	ASTM D1126
Turbidity	EPA 180.1
Specific Gravity	Modified ASTM 4052
Density	Modified ASTM 4052

Groundwater sampling methods to be employed, including sampling standard operating procedures, are as adapted from Striggow (2017) or as approved by the Director. Sample containers will be new and of an appropriate material and size for the analyte. Sufficient volumes will be collected to complete all of the specified analyses in Table 12. The appropriate preservation of each sample container will be completed upon sample collection (see QASP). Chain-of-custody will be documented using a standardized form from the analytical laboratory and will be retained and archived to allow tracking of sample status. This will include any required duplicates collected and appropriate field and trip blanks included for quality assurance. Completing the field chain-

of-custody form is the responsibility of groundwater sampling personnel.

8.2.3 Sampling Methods

The sampling system used to sample and quantify the freshwater constituents will consist of split samples obtained from the East Columbia Water District following their standard sampling methodology. Samples will be filtered and preserved using standard techniques and protocols for freshwater sampling. All sample containers will be labeled with durable labels and indelible markings. A unique sample identification number and sampling date will be recorded on the sample containers. The sample container will be sealed and sent to an authorized third-party laboratory.

8.2.4 Analysis Procedures and Chain of Custody

Samples will be analyzed by a third party laboratory accredited by the Louisiana Department of Environmental Quality (https://internet.deq.louisiana.gov/portal/divisions/lelap/accredited-laboratories) using standardized procedures. Detection limits will be dependent on equipment facilitated for the analytical methods by the selected qualified vendor and meet the minimum levels set forth in Appendix 1.

The sample chain-of-custody procedures will be dependent on vendor selection as they will assume the custody of the samples. The procedures will document and track the sample transfer to laboratory, to the analyst, to testing, to storage, to disposal (at a minimum). A sample chain-of-custody procedure is illustrated in Appendix 1.

9.0 EXTERNAL MECHANICAL INTEGRITY TESTING (MIT)

The Louisiana Green Fuels, Port of Columbia Facility will conduct at least one of the tests presented in Table 13 periodically during the injection phase to verify external mechanical integrity in each injection well as required at §146.89(c) and §146.90, LAC §3627.A.3 and 3625.A (State of Louisiana), and LCFS Protocol Subsection C.4.1(a)(7) and LCFS Protocol Subsection C.4.2. A demonstration of mechanical integrity will be made at least once a year during injection operations.

9.1 TESTING LOCATION AND FREQUENCY

The integrity of the long-string casing, injection tubing, and annular seal shall be tested by means of an approved pressure test for all injection wells. The integrity of the bottom-hole cement may be tested by means of a temperature survey or an approved tracer survey. Alternatively, a noise log may be run in the well to demonstrate containment within permitted injection zones. Pulsed neutron logging will be run to verify the mechanical integrity of the near-well area behind the casing.

Table 13. Mechanical Integrity Testing – Injection Wells

Test Description	Location
Temperature Survey **OR** Tracer Survey	Each Injection Well
	Each Injection Well
Pulsed Neutron Log	Each Injection Well
Annulus Pressure Test	Each Injection Well

Mechanical Integrity Tests (MIT's) will be run after the initial construction of the well prior to the initiation of injection operations. During injection operations the MITs will be performed on an annual basis within 45 days of the anniversary of the preceding year's test. The Louisiana Green Fuels, Port of Columbia Facility will notify the UIC Director ahead of testing. This schedule will repeat during the lifetime of the well during injection operations and prior to plugging operations. Should the well require a workover, an MIT will also be performed prior to placing the well back into service.

9.2 TESTING DETAILS

Prior to running an MIT, the wellbore annulus may be displaced with water or brine, in either case, the well will be allowed to thermally stabilize prior to all testing operations. It is recommended that the well be shut in for 36 hours to allow temperature effects to dissipate, with the exception of the Tuscaloosa/Paluxy Injection Zone. The external MIT logs will be run on all injection wells.

9.2.1 Temperature Survey

A baseline differential temperature survey will be run in the well after allowing the well a period of time to reach approximate static conditions. The temperature log is one of the approved logs for detecting fluid movement outside pipe. A baseline survey will be run during completion operations and will provide an initial baseline temperature curve for future comparisons. The log will include both an absolute temperature curve and a differential temperature curve. The well should be shut in at least 36 hours to allow for temperature stabilization prior to running the temperature survey.

If a distributed temperature sensing fiber is run in the injection wells, the fiber will be used for the temperature testing; otherwise, a wireline truck will be used.

If wireline operations are conducted, the temperature will be logged down from the surface to total depth in the well. Recommended line speed for the logging operations is 30 to 40 feet per minute. A correlation log(s) will be presented in track 1, and the two temperature curves will be presented in tracks 2 and 3. The temperature log will be scaled at or about 20° F (or 10° C degrees) per track. The differential curve will be scaled in a manner appropriate to the logging equipment design but will be sensitive enough to readily indicate temperature anomalies. In general, the procedure for wireline operations will be as follows:

1. Attach a temperature probe and casing collar locator (CCL) to the wireline.
2. After a minimum of 36 hours of well static conditions, begin the temperature survey. The tools will be lowered into well at 30 to 40 feet/minute, recording temperature in wellbore. The temperature survey will be run to the deepest attainable depth (top of solids fill) in the wellbore. The wireline may be flagged, if needed, to assist in depth correlation.

3. Following completion of the survey, the wireline tools will be retrieved from the wellbore.

A temperature log run will be considered successful if there are no unexplained temperature anomalies observed outside of the permitted injection zone.

Interpretation

Confirm the validity of the log at the well site by comparing logs made at or near the same site. When lithology and injectate characteristics are similar, then thermal effects along the well bore should also be very similar. After the temperature effects caused by casing joints, packers, well diameter, casing string differences, and cement have dissipated, the temperature profiles should be similar, although not identical. If construction features are evident, a longer shut-in period is probably needed.

Identification of flow is based on relative differences between logs periodically run in a well. The log can also be compared to temperature logs in other nearby wells, if such logs exist. Although the gradients may be quite different as a result of differing injection history, their relative positions should be obviously consistent. Lithologic effects which show up on one log should show up similarly in other wells at the same site. Failure of logs made at the same site under conditions which should result in thermal stability to compare coherently constitutes an anomaly.

If there are no logs suitable for comparison, then deviations from a predictable geothermal gradient are anomalies. These may take the form of a nearly constant temperature between reservoir strata. When more than one log is run, these anomalies are likely to grow (be left behind) as the profile returns toward the natural geothermal while relative differences between the traces elsewhere decrease. In addition areas with active flow will reach a stable temperature more quickly than other areas. If the movement is not related to injection, this temperature should be that of the natural geothermal gradient at the depth of the source reservoir.

If there are anomalies, a failure of mechanical integrity may be indicated. In such a case, an additional new log may be necessary to show whether forms apparent on the log just made are evolving toward the forms established on the log from another well. Comparison of these two

new logs should show increasing parallelism along the cased well bore, if not, then there may be flow along a channel adjacent to the well bore. If this flow results in the movement of liquid into unauthorized zones and/or between USDWs, then the well does not have mechanical integrity. In the event that there are unresolved anomalies that might indicate an absence of mechanical integrity, another approved method (radioactive tracer, noise, oxygen activation, or other logs approved by the UIC Director) must be used to confirm the absence of flow into unauthorized zones or between USDWs.

Identification of flow behind the casing is always made from long-term shut-in logs. The resolution of long-term shut-in logs for identifying the presence of flow is greater than that of logs made during injection. The temperature gradient within a well which has been injecting for some time is very shallow as the temperature at the injection zone may be only a few degrees different from that at the surface. The presence of a flow behind the casing will result in a fractional change in this gradient which will be proportional to the ratio of the flow rates within and outside the tubing. Therefore, only a rather substantial flow can be identified using logs made during injection.

If temperature anomalies are observed outside of the permitted zone, additional logging may be conducted to determine whether a loss of mechanical integrity or containment has occurred. Depending on the nature of the suspected movement, radioactive tracer, noise, oxygen activation, or other logs approved by the UIC Director may be required to further define the nature of the fluid movement or to diagnose a potential leak.

9.2.2 Radioactive Tracer Survey

A Radioactive Tracer Survey (RTS) may be run as an alternative to the temperature survey. The tool consists of a gamma detector above the ejector port and one or two detectors below the ejector port. In order to run the RTS, the wellbore annulus will need to be flushed with brine and the test will be conducted using brine to convey the radioactive iodine tracer material. The tool will continuously record gamma ray API units during tracer fluid ejection. The upper detector will be recorded in track 1 at a scale of 0 to 100 or 150 API units, and the lower detector(s) will be recorded in tracks 2 and 3 at a higher (less sensitive) scale, typically 0 to 1,000 API units.

Prior to testing, an initial gamma ray baseline log will be recorded from at least 100 feet above the injection tubing packer to total depth of the well. The initial gamma ray survey can be made under low flow conditions or with the well in static conditions.

A concurrent casing collar locator log for depth correlation will be run on the wireline tool string. Two five (5) minute time drive statistical checks will be run prior to the ejection of tracer fluid. One of the statistical checks will be run in a confining unit immediately above the uppermost perforation in the well. The second check should be run within the injection zone sandstone. The baseline log and statistical checks will be run to determine background radiation prior to tracer fluid ejection.

Brine injection will be initiated or increased during testing operations. During the survey, brine injection rates will be set at the rate at which the fluid will be under laminar flow conditions, while remaining within the maximum permitted operating parameters anticipated for the well. The volume of the tracer fluid slug will be sufficient to cause a gamma curve deflection on the order of 25x background reading as the ejected slug passes the lower detector(s). This would typically be a full-scale deflection.

A constant injection (moving) survey will be run from above the packer to the perforations to check for leaks between those two points. This survey will consist of ejecting a tracer slug above the packer, verifying the tracer ejection, dropping down through the slug, and then logging up through the slug to above where the slug was first ejected. The tool will be successively dropped down through the slug again, and logging will continue upward to above where the slug was encountered on the previous pass. This process will be repeated a minimum of two times, until the slug flows out into the formation. If necessary, the injection rate may be adjusted to accomplish this test.

A stationary survey will be run approximately 20 feet or less above the top of the perforated interval to check for upward fluid migration outside the cemented casing. Flow during the stationary surveys will be at sufficient rates to approximate normal operating conditions anticipated for the well. The procedure consists of setting the tool and logging on time drive, ejecting a slug, verifying the ejection, and waiting an appropriate amount of time that would allow the slug to exit the wellbore and return through channels outside pipe, if present. The time spent

at the station will vary but should be at least twice the time estimated to detect the tracer fluid if channeling existed, or for 15 minutes, whichever is greater. If tracer fluid is detected channeling outside of the pipe at any time during the stationary survey, then the survey may be stopped, and the tracer fluid's movement will be documented by logging up on depth drive, until the tracer exits the channel. The stationary survey should be repeated at least one time.

Additional stationary or moving surveys may be required, depending upon well construction, test results, or to investigate known problem conditions. At least two repeatable logs of every tracer survey, moving and stationary, should be run. On completion of the tracer surveys, a final background gamma log will be run for comparison with the initial background log. In general, the test procedure will be as follows:

1. Attach radioactive tracer tools, including casing collar locator (CCL), gamma ray detectors and ejector modules to the wireline. Lower tools in wellbore to deepest attainable depth (top of solids fill). Record the depth of solids fill in the well, if any. Correlate tools on depth with the injection packer and any other cased-hole log(s) run in the well.
2. A baseline gamma log will be run from deepest attainable depth to approximately 4,800 feet (must be at least 100 feet above the packer). Statistical tool checks will be conducted 10 feet above the set depth of the injection packer and approximately 15 feet above the top perforation. (*Specific depths will be identified ad updated after injection well(s) completion*).
3. With the tool set a minimum of 100 feet above the packer, start injecting brine fluid at approximately 50 gpm (or defined acceptable rate). Eject a slug of tracer material and verify ejection.
4. Lower the tool through the slug and log up through the slug. Repeat slug-tracking sequence, following the slug down the tubing and into the injection zone until the slug is dissipated.

Note: It is desired to achieve a minimum of three or more passes below the injection packer before the radioactive slug exits the perforations. Adjust or reduce injection rate if needed to achieve this objective.

5. Repeat Steps 3 and 4.

6. Position lower detector of RTS tool at approximately 15 feet above the top perforation. Initiate and maintain injection at approximately 250 gpm (or defined acceptable rate).
7. Eject a slug of tracer material and record on time drive for a minimum of 15 minutes to determine if upward flow around the casing occurs.
8. Repeat Step 7.
9. Cease pumping, lower the tool to the deepest attainable depth, and run a repeat baseline gamma ray log to verify that the radiation level has returned to background.
10. Dump remaining tracer material from the tool and pump remaining test fluid to flush the tracer material from the wellbore.
11. Retrieve the wireline tools from the wellbore and rig down wireline unit.

Interpretation

Where a measurable amount of tracer material leaks from the tubing, it will be observed as a small area of increased radioactivity after the slug has passed. If an area of elevated radioactivity is observed, additional runs should clarify what becomes of the RA material. This will demonstrate whether only the tubing is leaking, or if both the tubing and casing lack integrity. In most cases, if a well's casing has integrity but a tubing leak exists, pressure equalization and cessation of leaking will occur until a change in injection pressure allows the leak to resume. This is why it is important to ensure a pressure differential between the injection tubing and annulus.

If annulus pressure is lower than injection pressure and both the tubing and casing are leaking, any tracer material that leaks out of the tubing will generally move toward and out through the casing leak. This is because the annulus pressure normally will be higher than the hydrostatic pressures within adjacent formations at all depths. If only the tubing is leaking, the tracer material will remain near the leak, spreading slowly both up and down from the leak location.

Adherence of tracer material to the tubing can be differentiated from a tubing leak because any material adhering to the tubing will eventually be washed away with no movement evident.

If no evidence of leaking is observed, the well has demonstrated part 1 of MI. Be aware that demonstrations of MI using the RTS will be examined very closely, and any conditions which threaten the ability to interpret them accurately must be removed.

9.2.3 Alternative Mechanical Integrity Logging

Noise Log (if run)

Channels along well bores are very rarely uniform. When flow is occurring, irregularities in channel cross section usually result in generation of some turbulence which occurs in the audible range. Sonic energy travels for considerable distances through solids, allowing sensitive microphones to detect the effects of turbulent fluid flow at considerable distances. Different types of turbulence result in sounds having different frequencies. Single phase turbulence results in low frequency sounds, while two phase turbulence usually results in high frequency sounds. High pass filters are used to determine the intensity of detected noise within various frequency ranges.

Procedure

Noise logging may be carried out while injection is occurring in many wells because flow restriction caused by the logging tool is often insufficient to cause turbulence. It is especially desirable to log while injecting when looking for flow resulting from pressure increase near the top of the injection zone. If ambient noise while injecting is greater than 10 mv, injection should be halted. Logging procedures should include the following steps:

1. Make noise measurements at intervals of 100 feet to create a log on a coarse grid;

2. If any anomalies are evident on the coarse log, construct a finer grid by making noise measurements at intervals of 20 feet within the coarse intervals containing high noise levels;

3. Make noise measurements at intervals of 10 feet through the first 50 feet above the injection zone and at intervals of 20 feet within the 100-foot intervals containing:

    - the base of the lowermost bleed-off zone above the injection zone,
    - the base of the lowermost USDW, and
    - in the case of varying water quality within the zone of USDW, the top and base of each interval with significantly different water quality from the next interval;

4. Additional measurements may be made to pinpoint depths at which noise is produced; and

5. Use a vertical scale of 1 or 2 inches per 100 feet.

Interpretation

The interpretation of noise logs for the purpose of demonstrating mechanical integrity is quite straightforward. The following steps are used:

1. Determine the base noise level in the well (dead well level);

2. Identify departures from this level. An increase in noise near the surface due to equipment operating at the surface is to be expected in many situations;

3. Attempt to determine the extent of any movement, this may be difficult when there are few flow constrictions;

4. If flow is into or between USDWs, a lack of mechanical integrity is indicated. If flow is from the injection zone of a hazardous-waste disposal well into or above the confining zone, failure of containment is indicated.

If the log measurements are ambiguous, the determination should be confirmed using another method.

Oxygen Activation Log (if run)

The oxygen activation method is based on the ability of the tool to convert oxygen into Nitrogen$_{16}$ within a short distance of the tool. This is accomplished by emitting high energy neutrons from the tool's neutron source. N_{16} is an unstable isotope of nitrogen which is referred to as activated oxygen. The half-life of activated oxygen is just 7.13 seconds, and the release of gamma rays as the activated oxygen decays into oxygen can be measured. If the tool is stationary and oxygen is activated, detectors placed near the activator device will detect increased gamma radiation. The intensity of the additional radiation will be inversely

proportional to the square of the distance of the activated oxygen from the detector. Much of the oxygen near the tool occurs in water. If water containing activated oxygen moves, the measured intensity of radiation will be greater if the slug of activated oxygen moves closer to the detector, and less if it moves away. By comparison of intensity of gamma radiation measured as a result of activation at two detectors, the direction and velocity of water movement can be determined. Studies under controlled conditions have shown that water velocities between two and 120 feet per minute can be measured.

Procedure

All measurements should be taken for periods of at least five minutes with the well injecting at the maximum normal rate. A total of at least 15 minutes measurement time is required at each station. This total time may be accumulated in one, two, or three episodes. If open-hole caliper logs are available, care should be taken to obtain all readings at depths where the well bore is in gauge. The method for obtaining measurements shall conform to optimum procedures contained in the operator's manual for the tool being used. The following steps are recommended for demonstrating mechanical integrity using the oxygen activation log:

1. Secure a log for lithology determination. If no such log is available, run a gamma ray-neutron log to identify porous intervals;

2. If required for tool calibration, background checks will be run with no injection occurring in an interval where no flow is thought to occur. Background calibration should be run for each interval of varying well construction;

3. Take measurements at stations at least 10 feet above the open injection interval;

4. Take measurements at the top of the confining zone and at two or three formation changes between the confining zone and the base of the USDW;

5. Take measurements within 50 feet below the base of each USDW, within 50 feet of the top of the first underlying aquifer, and at least one measurement between these two points;

6. If anomalies are found, additional readings, including readings made while the well is injecting if the original measurements were made while not injecting, or not injecting if the original measurements were made while injecting, should be made above and below the depth of the anomaly to confirm the anomalous reading and discover the extent of fluid movement; and

7. If flow is indicated, another log may be used to confirm the measurement and define the extent of flow. The choice for the confirmation log should be based on all wellbore and environmental factors, and the tool choice must be approved by Region 5 prior to commencing testing operations.

Interpretation

A ratio of the short-spaced flow indicator result to standard deviation of 3 to 4:1 indicates flow. Indicated water-flow velocities should be in excess of two feet per minute, lower values should be viewed with skepticism. Velocities near and above two feet per minute have been measured at several depths at several sites in EPA Region 5, however, other logs did not indicate flow. In some cases the occurrences were repeatable, at least during the period of one logging episode. Although the cause of the false measurements is not known, it is assumed that the logging tool was not properly calibrated for the interval being tested.

To minimize false positives, it is recommended that all measurements be confirmed at several nearby depths and/or measurements be taken under a minimum of 3 varying injection rates, *i.e.* at 75%, 50%, and 25% of maximum permitted injection rates. Before costly measures are taken to remedy problems, their existence should be confirmed using another approved log.

9.2.4 Pulsed Neutron Logging

Pulsed neutron logging will be run to verify the mechanical integrity and to determine carbon dioxide saturations in the near-wellbore area behind the casing in the injection wells. A baseline survey will be run during completion operations (with the injection well in completion configuration) and will provide an initial baseline log for future comparisons. Should the downhole well completion change at any time, a new baseline log will be run. The pulsed neutron survey will be run from the Wilcox Formation below a depth of 2,400 feet below ground down to the total

depth of the well and will be run in gas-sigma-hydrogen mode. The sigma measurement is used to determine porosity, differentiate between saline water and carbon dioxide, and calculate formation saturation in the Tuscaloosa/Paluxy Injection Zone. The Port of Columbia Facility will run the Pulsed Neutron log annually for the first five years, and then every 5 years after that throughout the life of the wells. The UIC Director may be require more frequent monitoring to further define the nature of potential fluid movement along the casing-borehole wall or to diagnose potential leaks.

9.2.5 Annulus Pressure Test

In conjunction with annual mechanical integrity testing, an annulus pressure test of the casing by tubing annulus will be made.

Pressures will be recorded on a time-drive recorder for at least 60 minutes in duration and the chart or digital printout of times and pressures will be certified as true and accurate. The pressure scale on the chart will be low enough to readily show a 5 percent change from the starting pressure. In general, the test procedure will be as follows:

1. Connect a high-resolution pressure transducer to the annulus and increase annulus pressure to at least 200 psig over the permitted maximum tubing/injection pressure. Conduct Annulus Pressure Test (APT) by holding annular pressure a minimum of 100 psi above the well's maximum permitted surface injection pressure for a minimum of 60 minutes.
2. At the conclusion of the APT, annular pressure will be lowered to the well's normal, safe differential pressure value and pressure recording equipment will be removed from the well system.

A successful pressure test will "PASS" if the pressure holds to +/-5 percent of the starting pressure. **IF** the test isn't able to hold pressure for a selected time period, then the test will be considered a "FAIL". The test will be repeated and if the well continues to "FAIL", the construction of the well may have lost its integrity. Additional tests at progressively lower pressures may be run to identify the pressure at which the annulus can hold a differential. Continuous monitoring of the annulus system will be reviewed to identify if there are any data that may lead to a potential leak and assist in diagnosing potential issues with the annulus.

10.0 TRANSIENT PRESSURE FALLOFF TEST

The Louisiana Green Fuels, Port of Columbia Facility will perform pressure fall-off tests during the injection phase as described below to meet the requirements of 40 CFR §146.90(f), LAC §3625.A.6 (State of Louisiana), and LCFS Protocol Subsection C.2.3.1(i)(1) and LCFS Protocol Subsection C.4.1(a)(8). Pressure fall-off testing will be conducted upon completion of each injection well to characterize baseline formation properties, as well as determine near well/reservoir conditions that may impact the injection of carbon dioxide.

10.1 FALLOFF TESTING LOCATION AND FREQUENCY

The Louisiana Green Fuels, Port of Columbia Facility will perform an initial (baseline) pressure fall-off test in each injection well using brine or municipal water mixed with a clay stabilizer to avert clay swelling. This will allow for baseline characterization of the transmissibility to fluid within the Tuscaloosa/Paluxy Injection Zone. The initial pressure fall-off testing will be repeated using carbon dioxide within the first 60 days of initiation of injection operations. This will allow for comparison to the baseline fluid-to-fluid test with the change in the injection fluid from brine water to carbon dioxide.

A pressure fall-off test will be performed annually (within approximately +/-45 days of the anniversary of the previous test), at a minimum, during the first five years of injection and then at subsequent 5-year intervals, thereafter, for the lifetime of injection operations ((LCFS Protocol Subsection C.4.3.1.5). Periodic testing is expected to provide insight into performance of the Storage Complex and potentially aid in assessing the dimensions of the expanding carbon dioxide plume, based on the expected lateral change from supercritical carbon dioxide near the wellbore and native formation brine beyond the plume. The Director may request more frequent testing which will be dependent on test results. A final pressure fall-off test will be run after the cessation of injection into each injection well.

10.2 FALLOFF TESTING DETAILS

Testing procedures will follow the methodology detailed in "*EPA Region 6 UIC Pressure Falloff*

Testing Guideline-Third Revision (August 8, 2002)"[2]. Bottomhole pressure measurements near the perforations are preferred due to phase changes within the column of carbon dioxide in the tubing. A surface pressure gauge may also serve as a monitoring tool for tracking the test progress.

The pressure gauge can be either installed as part of the completion or can be deployed via a wireline truck. If a wireline truck deployed gauge is used, the wireline should be corrosion resistant (such as MP-35 line), and the deployed gauges should consist of a surface read-out gauge with a memory backup. Gauge specifications should be as follows or similar:

Table 14: Injection/Falloff Pressure Gauge Information – Wireline Testing Operations

Pressure Gauge	Property	Value
Surface Readout Pressure Gauge	Range Resolution	0 – 10,000 psi/356 ºF +/-0.01 psi/0.01 ºF
	Accuracy	+/-0.03% of full scale (+/-3 psi/+/-0.1 ºF)
	Manufacturer's Recommended Calibration Frequency	Minimum Annual
Memory Pressure Gauge	Range Resolution	0 – 10,000 psi/356 ºF +/-0.01 psi/0.01 ºF
	Accuracy	+/-0.03% of full scale (+/-3 psi/+/-0.1 ºF)
	Manufacturer's Recommended Calibration Frequency	Minimum Annual

The general testing procedure is as follows (and presumes that a wireline-deployed unit is used for the testing). **NOTE**: a dedicated downhole monitoring gauge may be used if installed on each of the injection wells:

1. Mobilize wireline unit to the injection well and rig up on wellhead.
2. Rig up a wireline lubricator containing a calibrated downhole surface-readout pressure gauge (SRO) with memory gauge installed in the tool string as a backup, to the adapter above the crown valve. Each gauge should have an operating range of 0 - 10,000 psi.

[2] https://www.epa.gov/sites/default/files/2015-07/documents/guideline.pdf

Reference the gauge to kelly bushing (KB) reference elevation as well as the elevation above ground level.

3. Open crown valve, record surface injection pressure, and run in hole with SRO to just above the shallowest perforations in the completion while maintaining injection at a constant rate. Steady rates of injection should be maintained for at least 24 hours ahead of the planned shut-in of the injection well. Any offset injection well(s) should be either shut-in ahead of the testing or should maintain a constant rate of injection for the entire duration of the testing. This will minimize cross-well interference effects.
4. With the SRO positioned just above the perforations, monitor the bottom-hole injection pressure response for ±1 hour to allow the gauge to stabilize (temperature and pressure stabilization). Ensure that the injection rate and pressure are stable.
5. Cease injection as rapidly as possible (controlled quick shut-in); close the control valve and the manual flowline valve at well site (start with the valve **closest** to the wellhead so that wellbore storage effect in early time is minimized). Conduct the pressure fall-off test for approximately 24 hours, or until bottomhole pressures have stabilized.
6. Lock out all valves on the injection annulus pressure system so that annulus pressure cannot be changed during the falloff period. Ensure that valves on flow line to the injection well are closed and locked to prevent flow to the well during the fall-off period.
7. After 24 hours, download data and make preliminary field analysis of the fall-off test data with computer-aided transient test software to estimate if or when radial flow conditions might be reached. If sufficient data acquisition is confirmed, end fall-off test. If additional data is required, extend fall-off test until radial flow conditions are confirmed. After confirmation of sufficient data acquisition, end fall-off test.
8. Pull SRO tool up out of the well at 1,000-foot increments and allow the gauge to stabilize (5 minutes each stop). Record stabilized temperature and pressure. Repeat the process to collect stabilized pressure data (5-minute stops) at 1,000-foot intervals and in the lubricator.

In performing a fall-off test analysis, a series of plots and calculations will be prepared to QA/QC the test, identify flow regimes, and determine well completion and reservoir parameters. It will

also be used to compare formation characteristics such as transmissivity and skin factor of the near wellbore for changes over time. Skin effects due to drilling and completion activities (due to possible damage from well perforation) will be assessed for the wells injectivity and potential well cleanouts in the future. Data reduction and analyses will follow USEPA Region 6's *UIC Pressure Falloff Testing Guidelines – Third Revision* (https://www.epa.gov/sites/default/files/2015-07/documents/guideline.pdf). These tests can also measure drops in pressure due to potential damage/leakage over time. In CO_2, it is anticipated that pressure drops may indicate multiple fluid phases. The analysis will be designed to consider all parameters.

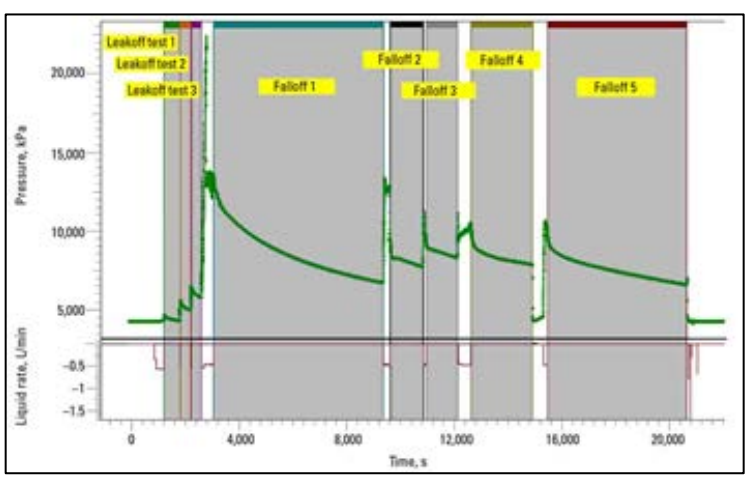
Reports will be submitted to the EPA within 30 days of the test [per 40 CFR §146.91 (e) and §146.91 (b)(3)].

10.3 FRACTURE/PARTING PRESSURE TESTING

Per LCFS Protocol Subsection C 2.3(a)(3)(A) ad C.2.3.1(h), the fracture/parting pressure of the sequestration zone and primary confining layer and the corresponding fracture gradients determined via step rate or leak-off tests must be performed in the wellbore. These testing and logging activities may be undertaken during the drilling of an injection or monitoring well(s) to determine the state of stress of the injection zone and caprock.

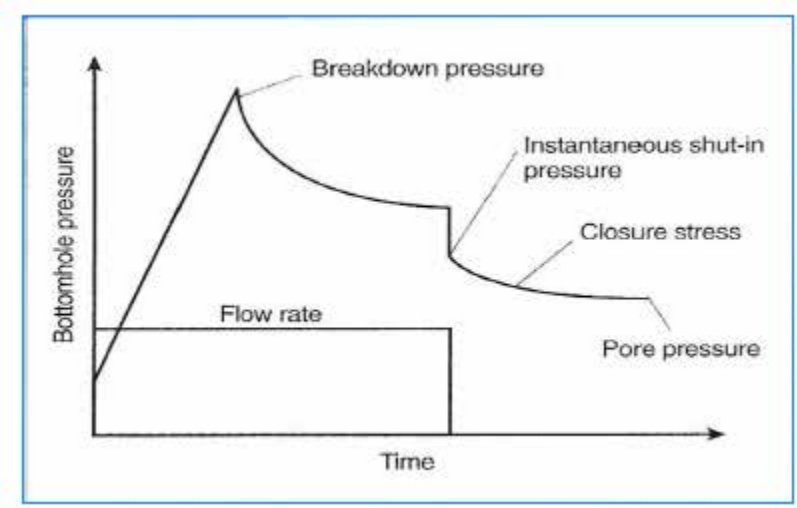
Mini-frac

During drilling of the injection and/or observation well(s), an open hole Schlumberger Modular Dynamics Tester (MDT), or equivalent, mini- frac will be completed to determine the minimum horizontal stress of the formation. The mini-frac operations will be performed using a dual packer setup and will be conducted on both the injection zone and overlying confining zone To determine the maximum horizontal stress. The adjacent illustration shows an annotated example of a typical testing



sequence that can be used to determine the propagation pressure, closure pressure, and reopening pressure, which then define the minimum horizontal stress in the subsurface.

Mini-frac testing will be conducted with the Schlumberger MDT tester in Dual-Packer Mode to determine the breakdown pressure gradient. For stress testing to provide accurate information on the state of stress and breakdown pressure for the injection zone and caprock, the tested interval must have no pre-existing weaknesses, such as natural fractures. Proposed test intervals will be screened with the Formation Imager Tool to select packer setting depths for testing.



Diagnostic Fracture Injection Test (DFIT) - Confining Zone

In a diagnostic fracture injection test (DFIT), a relatively small volume of fluid is injected into the subsurface, creating a hydraulic fracture. The testing is essentially similar to the mini-frac test, but the test is conducted in the open hole or the cased hole with dual packers straddling the test interval. After the end of injection, the pressure in the wellbore is monitored for durations of hours to days. The pressure measurements from the injection and recovery periods are used to infer properties of the formation, including the leakoff coefficient, permeability, fracture closure pressure (which is related to the magnitude of the minimum principal stress and the net pressure), and formation pressure.

During the initial injection period, where a fracture has not formed and wellbore storage controls the pressure behavior, pressure increases with increasing injection volume. At formation breakdown, a fracture is initiated in the formation. At breakdown, either a new fracture will be created causing a decrease in pressure or expansion of an already existing fracture will cause a pressure plateau. Following breakdown, continued injection causes the fracture to extend out into the formation (propagation pressure), reached at #3, and the ISIP (initial shut-in pressure) is

reached at #4. DFIT analysis is primarily interested in analyzing the trends in pressure that occur in the hours and days after shut-in.

The DFIT procedure shall be as follows:

1. In a cased hole, perforate the well (small interval or full set).
2. Install high-resolution surface electronic memory gauges on wellhead and run high-resolution gauges downhole (set recording rate set to 1 second intervals). High resolution gauges will ensure that all pressure changes are recorded (recommend 0.1 to 0.001 psi psi gauge resolution.
3. Load hole with water (KCl or brine water with minimal additives as needed (avoid clay swelling etc.)) to fill up the wellbore.
4. Start recording before pumping starts and end recording after the fall-off (pressure recovery) is complete.
5. Start the pump to start injection and record the flow rates. The injection rate should be high enough to breakdown the perforations and create a small fracture. After breakdown, fluid rate should be increased up to maximum pressure limit and injection should be constantly pumped at a steady rate for 3 to 5 minutes.
6. Step down to 75%, 50%, and optionally 30% of maximum rate. Each step down can be as short as 10 seconds
7. Shut-down the pump quickly, recording the total volume pumped, and isolate the wellhead.
8. Rig down the pumping equipment without disturbing the isolated electronic gauges.
9. Collect the data from the pump unit as well as the acquisition setup.

Step-rate Testing - Injection Zone

Step-rate testing is fundamentally similar to mini-frac testing but is performed in the full wellbore using open hole packers set on work string while injection is provided by a pumping unit. Per LCFS Protocol Subsection C 2.3(a)(3)(A), a step-rate test must meet the following requirements:

1. Real-time downhole pressure recording must be employed;
2. Bottom-hole pressure must be recorded at a zero-injection rate for at least one full time step before the first step of the step rate test, and before one full time step after the last step

of the step rate test; and

3. Step rate test data reported must be raw and unaltered, and include the injection rate, bottom-hole pressure, surface pressure, pump rate volume, and time recorded continuously at a rate of every one second during the step rate test.

General procedures for step-rate testing is contained in "*EPA Region 8 Step-rate Test Procedure (January 12, 1999"*[3].

10.4 FRACTURE TEST ANALYSIS

The analysis of mini-frac test data is performed in two parts: pre-closure analysis and after-closure analysis. Pre-closure analysis consists of identifying closure and analyzing the early pressure falloff period while the induced fracture is closing. One of the most critical parameters in fracture treatment design is the closure pressure.

The following parameters are determined from the post-closure analysis:

- Fracture closure pressure (pc)
- Instantaneous Shut-In Pressure (ISIP) = Final injection pressure - Pressure drop due to friction
- ISIP Gradient = ISIP / Formation Depth
- Closure Gradient = Closure Pressure / Formation Depth
- Net Fracture Pressure (Δpnet) – Net fracture pressure is the additional pressure within the frac above the pressure required to keep the fracture open. It is an indication of the energy available to propagate the fracture.
    - Δpnet = ISIP - Closure Pressure
- Fluid efficiency – Fluid efficiency is the ratio of the stored volume within the fracture to the total fluid injected. A high fluid efficiency means low leak-off and indicates the energy used to inject the fluid was efficiently utilized in creating and growing the fracture. **L**ow leak-off is also an indication of low permeability. For mini-frac after-closure analysis,

[3] https://www.epa.gov/sites/default/files/2015-08/documents/r8_guideline_-_step_rate_testing.pdf

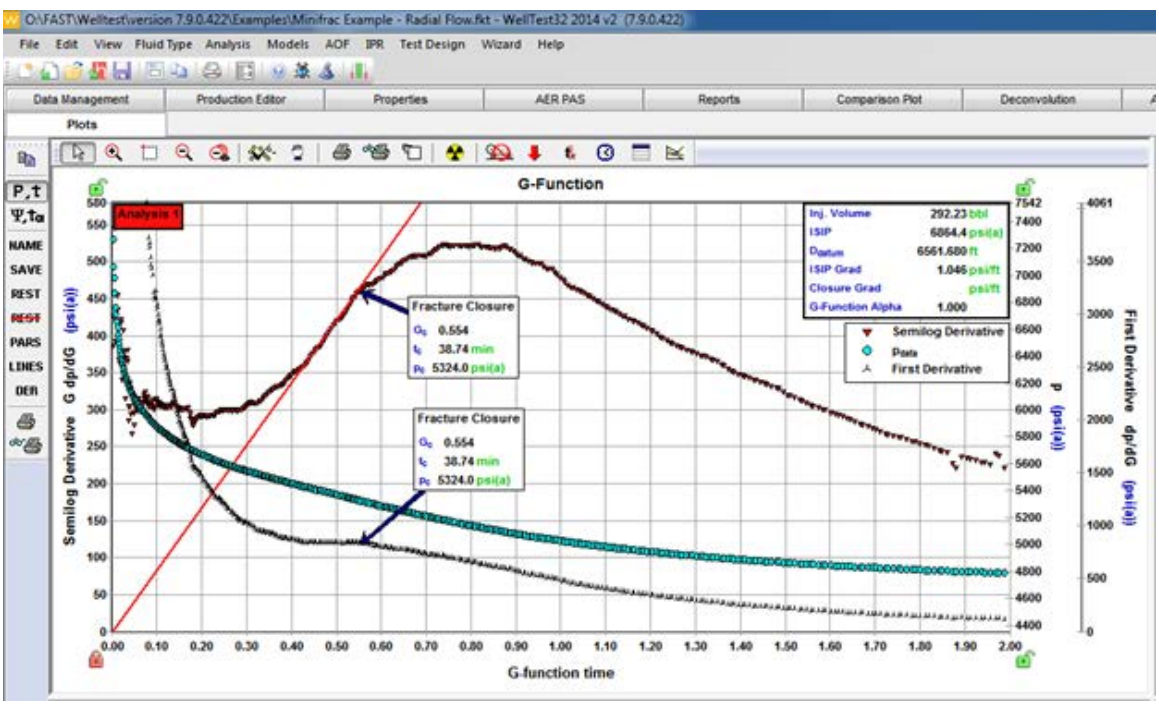
high fluid efficiency is coupled with long closure durations and even longer identifiable flow regime trends

- Gc is the G-function time at fracture closure
- Formation leakoff characteristics and fluid loss coefficients.

G-Function Analysis

Post-injection (pre-closure) pressure falloff analysis can be performed using the "G-function" and root time methods. The G-function is a dimensionless time function designed to linearize the pressure behavior during normal fluid leak-off from a bi-wing fracture. Any deviations from this behavior can be used to characterize other leak-off mechanisms. The root time plot exhibits similar behavior and can be used to support the G-function analysis.

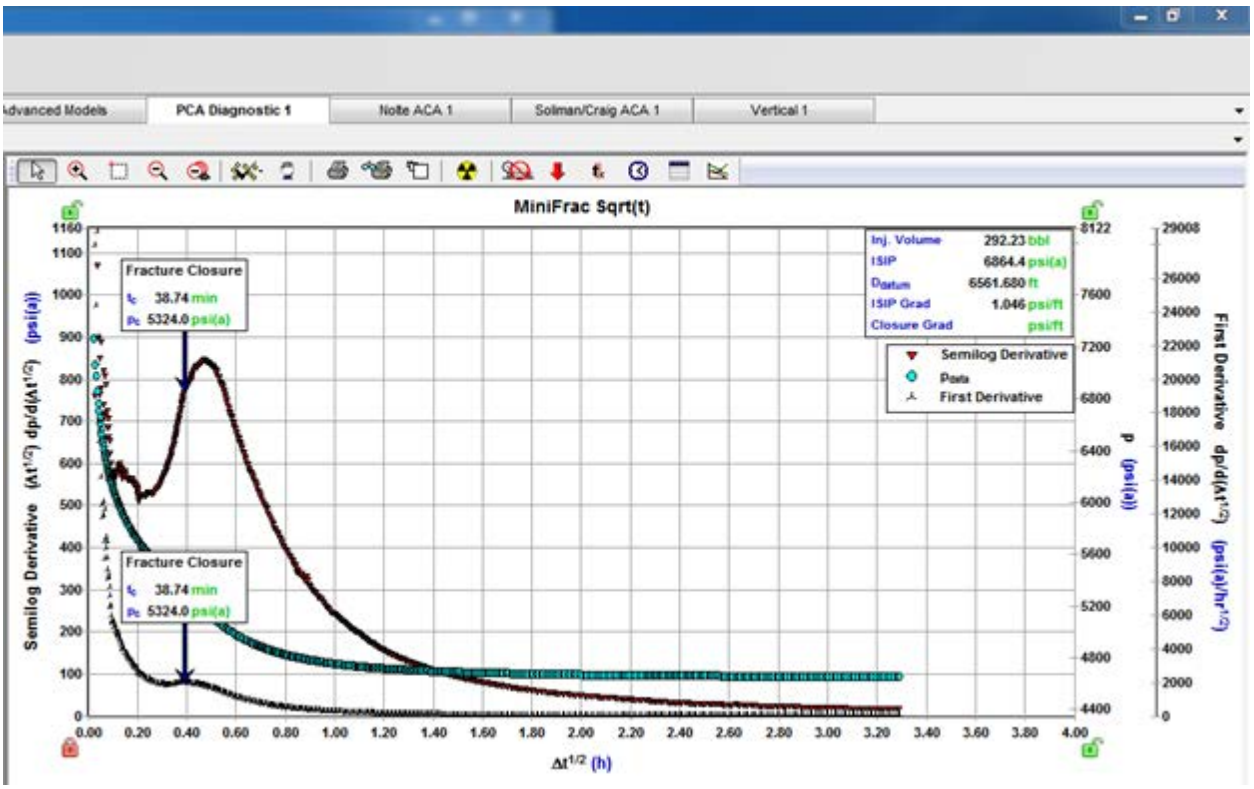
A straight-line trend of the G-function derivative (Gdp/dG) is expected where the slope of the derivative is still increasing. Position the Fracture Closure Identification line, which is anchored to the origin by default, through the straight-line portion of the G-Function derivative. Fracture closure is identified as the point where the G-Function derivative starts to deviate downward from the straight line as shown in the following graphic.



https://www.ihsenergy.ca/support/documentation_ca/WellTest/content/html_files/analysis_types/minifrac_test_analyses/minifrac-pre-closure_analysis.htm

Square Root Time Analysis

Fracture closure can be identified by the peak of the first derivative on the sqrt(t) plot, which corresponds to an inflection point on the pressure curve. The semi-log derivative behaves similar to the G-Function Analysis. A user-defined (Sqrt(t)) analysis line may be added to the sqrt(t) plot to help identify the point of inflection.



https://www.ihsenergy.ca/support/documentation_ca/WellTest/content/html_files/analysis_types/minifrac_test_analyses/minifrac-pre-closure_analysis.htm

Fluid Leakoff Types

The G-Function plots can be used to determine the type of leak-off during the testing. Four common leak-off types are:

1. Normal leak-off occurs when the fracture area is constant during shut-in and the leak-off occurs through a homogeneous rock matrix, diagnosed by:
    - A constant pressure derivative (dP/dG) during fracture closure.
    - The G-Function derivative (G dP/dG) lies on a straight line that passes through the origin.

2. Pressure-dependent leak-off (PDL) indicates the existence of secondary fractures intersecting the main fracture and is identified by a characteristic "hump" in the G-Function derivative that lies above the straight line fit through the normal leak-off data. This hump indicates fluid is leaking off faster than expected for a normal bi-wing fracture. The interception of secondary fractures, which could be natural or induced, facilitates this additional leak-off by providing a larger surface area exposed to the matrix.

    - A characteristic large "hump" in the G-Function derivative; G dP/dG lies above the straight line that passes through the origin.
    - Subsequent to the hump, the pressure decline exhibits normal leakoff.
    - The portion of the normal leakoff lies on a straight line passing through the origin.
    - The end of the hump is identified as "fissure opening pressure".

3. Transverse Storage/Fracture Height Recession is determined when the G-Function derivative G dP/dG falls below a straight line that extrapolates through the normal leak-off data, exhibiting a concave up-trend. This indicates fluid is leaking off slower than expected for a normal bi-wing fracture and suggests that the fracture has some pressure support. Two scenarios can explain this trend as discussed below.

    - Transverse storage occurs when the main fracture intercepts a secondary fracture network, which could be natural or induced. This differs from pressure-dependent leak-off in that the dominant effect of the secondary fractures is to provide pressure support to the main fracture, rather than additional surface area for leak-off. There can be cases where transverse storage (pressure support) dominates, followed by a period of pressure-dependent leak-off before closure of the main fracture occurs.

    - Fracture height recession occurs if the fracture propagates through adjoining impermeable layers (above or below the test zone) during injection. In the normal leak-off scenario, fluid can leak off from the entire surface area of the fracture. For fracture height recession, leak-off can only occur in the portion of the fracture which is in communication with the permeable zone. As a result, the leak-off rate

is slower than the normal case. Eventually, the fracture area in the impermeable layer(s) starts closing (height recession), and during this period the rate of pressure decline increases. Once the fracture height recedes to the edge of the permeable zone, the entire area of the frac contributes to leak off, and a period of normal leak-off ensues.

4. Fracture tip extension occurs when a fracture continues to grow even after injection is stopped and the well is shut-in. It is a phenomenon that occurs in very low permeability reservoirs, as the energy which normally would be released through leak-off is transferred to the ends of the fracture resulting in fracture tip extension. The characteristic signatures for a fracture tip extension are:

    - The G-Function derivative G dP/dG initially exhibits a large positive slope that continues to decrease with shut-in time, yielding a concave-down curvature.

    - Any straight line fit through the G-Function derivative G dP/dG intersects the y - axis above the origin.

Until the main fracture closes, the G-Function derivative behaves similarly to PDL, and it is difficult to distinguish between PDL and fracture tip extension.

11.0 CARBON DIOXIDE PLUME AND PRESSURE FRONT TRACKING.

The Louisiana Green Fuels, Port of Columbia Facility will employ both direct and indirect methods to track the geometry and extent of the carbon dioxide plume with time and the areal distribution in pressures within and above the Sequestration Complex to meet the requirements of 40 CFR §146.90(g), LAC §3625.A.7 (State of Louisiana), and LCFS Protocol Subsection C.4.1(a)(9)(A).

Table 15: Pressure-front and Plume-front Monitoring - Direct

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
PRESSURE-FRONT MONITORING-DIRECT				
Tuscaloosa/Paluxy Injection Zone	Pressure & Temperature	Injection Wells & 2 Monitor Wells	Injection Well Field & 10,152 feet up dip and 5,273 feet southeast	Continuous
AZMI Annona Sand	Pressure & Temperature	2 Monitor Wells	10,152 feet up dip and 5,273 feet southeast	Continuous
ACZMI Wilcox Sand	Pressure & Temperature	1 Monitor Well	Port of Columbia Facility	Continuous
PLUME-FRONT MONITORING-DIRECT				
Tuscaloosa/Paluxy Injection Zone	Fluid Sampling	2 Monitor Wells	10,152 feet up dip and 5,273 feet southeast	Adaptive, if triggered
AZMI Annona Sand	Fluid Sampling	2 Monitor Wells	10,152 feet up dip and 5,273 feet southeast	Adaptive, if triggered
ACZMI Wilcox Sand	Fluid Sampling	1 Monitor Well	Port of Columbia Facility	Baseline and quarterly, adaptive, if triggered
Freshwater Aquifer	Fluid Sampling	Public Water Supply Wells	Area of Review	Baseline and quarterly, adaptive, if triggered

Table 16: Pressure-front and Plume-front Monitoring - Indirect

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
PRESSURE-FRONT MONITORING-INDIRECT				
NONE				
PLUME-FRONT MONITORING-INDIRECT				

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Tuscaloosa/Paluxy Injection Zone	Pulsed Neutron	Injection Wells & 2 Monitor Wells	Injection Well Field & 10,152 feet up dip and 5,273 feet southeast	Annually in Injection Wells Years 1 to 5 and every 5 years thereafter Adaptive, if triggered at Monitor Wells
AZMI Annona Sand		Injection Wells & 2 Monitor Wells	Injection Well Field & 10,152 feet up dip and 5,273 feet southeast	Annually in Injection Wells Years 1 to 5 and every 5 years thereafter Adaptive, if triggered at Monitor Wells
ACZMI Wilcox Sand		Injection Wells & 2 AZMI Monitor Wells, 1 ACZMI Monitor Well	Injection Well Field & 10,152 feet up dip and 5,273 feet southeast, Wilcox Monitor on Facility	Annually in Injection Wells Years 1 to 5 and every 5 years thereafter Adaptive, if triggered at Monitor Wells
Tuscaloosa/Paluxy Injection Zone	Temperature	Injection Wells	Injection Well Field	Annually in Injection Wells Years 1 to 5 and every 5 years thereafter
AZMI Annona Sand		Injection Wells	Injection Well Field	Annually in Injection Wells Years 1 to 5 and every 5 years thereafter
ACZMI Wilcox Sand		Injection Wells	Injection Well Field	Annually in Injection Wells Years 1 to 5 and every 5 years thereafter
Sequestration Complex	Time-lapse Seismic	Injection Wells	CO_2 Plume	Dependent on Method Chosen

11.1 PLUME FRONT

11.1.1 Plume Monitoring Location and Frequency

Table 17 summarizes the methods that the Louisiana Green Fuels, Port of Columbia Facility will

use to monitor the migration of the sequestered carbon dioxide plume, including the activities, locations, and frequencies that will be employed. The parameters to be analyzed as part of fluid sampling in the Tuscaloosa/Paluxy Injection Zone and associated analytical methods are presented in Table 18.

Quality assurance procedures for these methods are presented in Appendix 1.

Direct monitoring in wells completed into the Tuscaloosa/Paluxy Injection Zone will be used to detect and define the dimensions of the carbon dioxide plume during well operations (LCFS Protocol Subsection C.4.1(a)(9)). The stratigraphic test well and the four abandoned oil and gas wells will be re-entered, deepened (if necessary), and repurposed by completion across the entire Tuscaloosa/Paluxy sandstone interval. Several of these wells are optimally located in the direct plume path of the sequestered carbon dioxide. The other monitor wells are located in and around the anticipated dimensions of the carbon dioxide plume. Real-time, continuous pressure monitoring will be performed in the wells, which will be configured to allow for fluid sampling, if needed, in the event carbon dioxide reaches the wellbore. Monitoring will also leverage the installed Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well, located approximately 5,273 feet southeast and down dip of the facility. This well will also be fitted with downhole pressure gauges (gauges will be referenced to ground level at each well) and will be configured to allow for fluid sampling, if needed, in the event carbon dioxide reaches the wellbore. Each well will also have a transmitter gauge at surface to continuously record tubing pressure. Experience from previously-implemented carbon capture and sequestration projects indicates that carbon dioxide will rapidly evacuate the wellbore fluids in a monitoring well that is open to the Injection Zone, which will result in increased wellhead pressures due to the lighter column of gas replacing the brine fluid column.

11.1.2 Plume Monitoring Details

Indirect plume monitoring in the Tuscaloosa/Paluxy Injection Zone will include pulsed neutron capture logging to monitor the lateral and vertical saturation in carbon dioxide. The Port of Columbia Facility is also considering the use of certain time-lapse seismic techniques, as the substitution of CO_2 for brine within sandstones at similar project depths is well documented to produce a strong negative change in acoustic impedance. Leading-edge techniques for time-lapse

imaging of carbon dioxide plume include time-lapse walk away vertical seismic profiling, azimuthal vertical seismic profiling, and/or sparse array walk-away surveys. At a minimum, the acoustic source sites will be oriented along the maximum and minimum orientations of the modeled plume and will be adjusted following each survey results. Distributed acoustic sensing (DAS) fiber may be installed in the injection well, which will facilitate data acquisition activities. Baseline and subsequent time-lapse surveys will be processed using a technique that will resolve the differences between the surveys, which will be mapped to show the change in plume extent over time.

Table 17 Summary of analytical and field parameters for fluid sampling in the Tuscaloosa/Paluxy Injection Zone

Parameters	Analytical Methods
Tuscaloosa/Paluxy Formation	
Dissolved CO_2 gas by headspace	Gas Chromatography (GC)
Dissolved CH_4 gas by headspace	Gas Chromatography (GC)
Hydrocarbons	Gas Chromatography (GC)
Dissolved inorganic carbon	Combustion
Bicarbonate	Titration
$\delta D\ CH_{24}$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$\delta C^{13}\ CO_2$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$\delta C^{13}\ CH_4$	Gas chromatography combustion isotope ratio mass spectrometry (GC/C/IRMS)
$C^{14}\ CO_2$	Accelerated mass spectrometry (AMS).
C^{14} Methane	Accelerated mass spectrometry (AMS).
Isotopic composition of selected major or minor constituents (*e.g.*, Sr $^{87/86,}$ S)	Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS)
Cations: Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Pb, Sb, Se, Si, Ti, Zn,	ICP-MS or ICP-OES, ASTM D5673, EPA 200.8 Ion Chromatography, EPA Method 200.8, ASTM 6919
Anions: Br, Cl, F, NO_3, SO_4,	Ion Chromatography, EPA Method 300.8, ASTM 4327
Total Dissolved Solids	EPA 160.1, ASTMN D5907-10
Alkalinity	EPA 310.1
pH (field)	EPA Method 150.1
Specific Conductance (field)	EPA 120.1, ASTM 1125

Parameters	Analytical Methods
Temperature (field)	Thermocouple
Hardness	ASTM D1126
Turbidity	EPA 180.1
Specific Gravity	Modified ASTM 4052
Density	Modified ASTM 4052

11.2 PRESSURE FRONT

11.2.1 Pressure Front Monitoring Location and Frequency

Table 18 presents the methods that the Louisiana Green Fuels, Port of Columbia Facility will use to monitor the position of the pressure front, including the activities, locations, and frequencies that the Port of Columbia Facility will employ.

Quality assurance procedures for these methods are presented in Appendix 1.

Direct pressure monitoring in the Tuscaloosa/Paluxy Injection Zone will be used to measure the injection induced pressure buildup with time in the Sequestration Complex. Pressure monitoring using down-hole pressure/temperature gauges, will be conducted in each of the active injection wells. Gauges will be referenced to ground level at each well. These monitor points will be used to evaluate the pressure buildup with time within the injection well field. Additionally, direct pressure and temperature monitoring will be conducted in five project monitoring wells completed into the Tuscaloosa/Paluxy Injection Zone. Several of the monitor wells are optimally located in an updip location within the expected plume path of the sequestered carbon dioxide. Real-time, continuous pressure and temperature monitoring will be performed in the well. Additionally, the installed Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well, located approximately 5,273 feet southeast and down dip of the facility will be used for monitoring and early detection of the injected carbon dioxide. These monitor points will also be used to evaluate the pressure decay with distance away from the injection well field (i.e., monitor the pressure front). The wells will also be fitted with downhole pressure gauges (gauges will be referenced to ground level at each well) and will be configured to allow for fluid sampling, if needed.

Table 18 Summary of Monitoring Intervals Depths – Below Ground Level Reference

Monitoring Zone	Port of Columbia Facility (feet BGL)	Whitetail Operating, Louisiana Green Fuels #1 (feet BGL)	Bradford-Brown Trust, Shipp No. 1 (feet BGL)
Wilcox ACZMI Zone	2,846 to 2,866	-Not Monitored-	-Not Monitored-
Annona AZMI Zone	-Not Monitored-	4,135 to 4,175	3,742 to 3,762
Tuscaloosa/Paluxy Injection Zone	4,764 to 5,484	4,895 to 5,615	4,400 to 5,120 est.

These measured pressures from the injection wells and the offset monitor locations will be used to assess the performance of the Tuscaloosa/Paluxy Injection Zone to ensure that the project is operating as permitted and will form the basis for the periodic re-evaluation of the extent of the Area of Review. Recorded pressures at the injection wells and the monitor locations will be compared to model predictions to determine if actual data deviate from baseline predictions. Significant departures of actual pressure data above model predictions will be used to trigger an adaptive re-assessment of the Area of Review, in addition to the minimum 5-year re-assessment time frame specified for periodic review. In addition to a re-assessment of the Area of Review, real-time data from the overlying monitoring will also be re-evaluated to ensure continued containment of the injected carbon dioxide within the Sequestration Complex.

The locations of the injection wells (bottomhole locations) and Tuscaloosa/Paluxy Injection Zone monitoring wells are shown in Figure 2. The anticipated plume geometry and the Area of Review Pressure Front with time are presented in Module B - Area of Review and Corrective Action.

The downhole pressure and temperature data will be transmitted to the distributed control system for evaluation and storage. A data archiver may be used to permanently store data sets for later recovery.

Table 19: Minimum Gauge Specifications – Downhole Gauges

Pressure Gauge	Property	Value
Surface Readout/Downhole Pressure Gauge	Range Resolution	0 – 10,000 psi/125 ºC +/-0.1 psi/0.01 ºC

	Accuracy	+/-0.2% of full scale-Pressure +/-0.5% of full scale-Temperature
	Gauge Stability	+/-0.2% of full scale per Annum

11.2.2 Pressure Front Monitoring Details

The Port of Columbia Facility will measure injection pressure buildup in the Tuscaloosa/Paluxy Injection Zone in each of the installed facility wells. Additionally direct monitoring of the pressure buildup at distance away from the point of injection will be monitored with two in-zone monitor wells:

1) Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well (SN975841), located 5,273 feet southeast and down dip of the injection wells, and
2) Bradford-Brown Trust Shipp No. 1 (SN137783) well, located approximately 10,152 feet north and up dip of the facility;
3) Bass Keahey No.1 (SN165395) well, located approximately 13,730 feet northeast and up dip of the facility;
4) Southern Carbon USA No. 1 (SN34225) well, located approximately 37,850 feet east- southeast of the facility; and
5) Murphy Meredith No. 1 (SN23356) well, located approximately 28,150 feet east-southeast of the facility.

These wells will provide control/monitor points along the developed pressure decay curve extending outward in the injected sandstones. In addition to the In-zone monitoring, shallower monitoring of both the Annona Sand (AZMI Monitor Zone) and the basal Wilcox sandstone (ACZMI Monitor Zone) will provide early detection of any potential upward movement of carbon dioxide and/or formation brines out from the Tuscaloosa/Paluxy Injection Zone. The Annona Sand monitoring provides a “first line of defense” within the Sequestration Complex, while the Wilcox monitoring provides a “second line of defense” for protection of the USDWs. Collectively, the direct monitoring program ensures protection of USDWs above the Sequestration Complex.

Table 20: Pressure front monitoring activities

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Tuscaloosa/Paluxy	Downhole pressure monitoring	Facility Injection Wells	Well Field	Real time daily read out.
Tuscaloosa/Paluxy	Downhole pressure monitoring	2 offset Monitoring Wells	Over area of review	Real time daily read out.
Annona	Downhole pressure monitoring	2 offset Monitoring Wells	Over area of review	Real time daily read out.
Wilcox	Downhole pressure monitoring	1 Onsite Monitoring Wells	Over area of review	Real time daily read out.

12.0 SURFACE AND NEAR-SURFACE MONITORING

The Louisiana Green Fuels, Port of Columbia Facility will monitor the surface and near-surface for potential carbon dioxide leakage, in accordance with applicable regulations and guidelines set forth by the EPA UIC program for Class VI injection well sites (40 CFR §146.90(h); EPA, 2013a;b; EPA, 2016; LAC Title 43 Part XVII §3625(A)(8) (State of Louisiana)), and LCFS Protocol Subsection C.4.1(a)(11).

The primary objective of the surface and near-surface monitoring program is to confirm containment of carbon dioxide within the deep subsurface to: 1) demonstrate no endangerment to public health or the environment, 2) confirm conformance with the proposed injection plan, and 3) validate calculations of total sequestered carbon dioxide in the deep subsurface. Accordingly, the proposed surface and near-surface program includes the following elements: i) determine baseline physical and chemical conditions and natural background variability at the surface above the storage complex, ii) detect changes in conditions that might be indicative of an environmental impact and therefore warrant further investigation, iii) attribute those changes to either natural variability or actual anthropogenic impacts, and iv) if needed, assist in the quantification and subsequent remediation of the potential carbon dioxide leak.

The proposed surface and near-surface monitoring program consists of three key monitoring components during the baseline and/or operational phases of the project: 1) atmospheric monitoring, 2) ecosystem stress monitoring, and/or 3) soil gas monitoring. These monitoring components will allow for early detection of potentially anomalous levels of carbon dioxide and other gases at the surface and/or near-surface. Details regarding each monitoring component are provided below.

12.1 ATMOSPHERIC MONITORING

Atmospheric monitoring may be used to identify carbon dioxide concentrations above ambient background levels and help determine locations of potential carbon dioxide leaks (NETL, 2009). Per Standard 40 CFR §146.90(h) and LCFS Protocol Subsections C.2.5(c)&(d) and C.4.3.2.2(d)&(e), continuous and intermittent atmospheric monitoring at the surface above the

storage complex during the baseline and operational phases of the project will be conducted to i) define the baseline physical and chemical atmospheric conditions at the surface above the storage complex, ii) characterize natural background variability, including seasonal and diurnal trends, and iii) detect potential atmospheric carbon dioxide leakage and/or potential movement of carbon dioxide that may endanger the local USDW, the Cockfield Aquifer.

Continuous air monitoring will be conducted utilizing eddy covariance flux measurement techniques via an advanced, stationary LI-COR® air quality and weather observation tower, equipped with eddy covariance (EC) and bio meteorological detectors. Intermittent atmospheric monitoring will be conducted at additional locations throughout the Area of Review utilizing a portable, handheld Landtec® infrared detector to supplement the continuous EC system monitoring data.

12.1.1 Monitoring Location and Frequency

The advanced LI-COR® EC system has an aerial coverage of up to 2- to 2.5-mile radius; therefore, a single tower set to a height of approximately 30 feet will be positioned at the location of the initial injection well (INJ #1) to provide site-wide monitoring of the Area of Review (see Figure 3). The EC system will collect data on a continuous basis during the 1- to 2-year baseline period and the estimated 20-year operational period.

Intermittent ground-surface gas concentrations will be manually collected monthly and quarterly during the baseline and operational phases, respectively, by a qualified vendor. Intermittent atmospheric monitoring will be conducted at locations of proposed injection wells, monitoring wells, and soil gas monitoring sites.

Due to the absence of deep artificial penetrations (e.g., oil and gas wells; see Figure 3) and other potential point sources (e.g., faults; see Section 2.0), additional continuous or intermittent atmospheric monitoring locations are not anticipated. During the post-injection site care phase, supplemental continuous and/or intermittent atmospheric monitoring may be considered as part of a post-injection site care leak detection strategy, based upon final approval of the demonstration of plume stability.

12.1.2 Analytical Instrumentation and Procedures

As further described below, LI-COR® EC systems are a low-impact, non-invasive technology that include precision, high-speed instruments capable of analyzing various near-surface and surface parameters (e.g., total gas concentrations, ambient carbon dioxide concentrations). The high-frequency data collected by the EC system are used to facilitate automated calculations of the net gas exchange (flux) between the ecosystem and the atmosphere. The EC tower will be fitted with the following instrumentation to analyze total gas concentrations, meteorological conditions, and soil conditions:

- LI-7500DS open-path CO_2/H_2O infrared gas analyzer and pressure transducer (barometric pressure);
- LI-7700 open-path CH_4 analyzer;
- LI-7820 N_2O trace gas analyzer;
- Gill R3-50 3-axis ultrasonic anemometer for the measurement of wind direction and speed; and
- Biomet sensors for the analysis of soil moisture and temperature (Hydra Probe II soil sensor), soil heat flux (Hukseflux HFP01 thermal sensor); relative humidity (Vaisala HUMICAP® 180R sensor), precipitation (TR-525M Rainfall Sensor), and ambient temperature (HMP155 probe), and net radiation across the surface (Kipp & Zonen NR-Lite).

The raw data from the EC system will be processed utilizing EddyPro® software and the on-site SmartFlux® System to derive representative real-time flux data for the Site. Tovi® Software will then be utilized to post-process the EC flux data, which will provide consistent, reproducible, and transparent data collection.

The Landtec® portable, handheld GEM2000 landfill gas analyzer is a simple, direct measurement technology that is capable of analyzing for ambient CO_2, CH_4, and O_2 concentrations (as percent volume) in the atmosphere and requires no data processing or post-processing. The portable gas analyzer will be calibrated regularly to a gas standard according to manufacturer specifications per the attached QASP.

Local ambient air carbon dioxide concentrations can vary spatially and temporally depending on factors including vegetation, changes in soil respiration, changes in atmospheric pressure, and the presence of other industrial processes (NETL, 2009). In addition, global atmospheric carbon dioxide concentrations are projected to rise an additional 9% over the next 18 years, from 412.5 ppm presently to ~450 ppm in 2040 (NASA, 2022). To better identify false-positive carbon dioxide detections, the presence of natural (e.g., soil and vegetation) and anthropogenic (e.g., industrial processes) sources of carbon dioxide in the vicinity of the site will need to be well understood during the life of the project (NETL, 2009). A routine inventory of (i) potential anthropogenic carbon dioxide sources unrelated to carbon dioxide leakage from the target reservoir (e.g., nearby industrial facilities, pipelines), (ii) oil and gas-related production or injection wells, and (iii) an assessment of nearby land use classifications and recent development activities will be conducted on an annual basis within a 4-mile radius of the initial injection well. As discussed below in Section 12.3, natural near-surface sources of carbon dioxide (e.g., microbial respiration, carbonate dissolution, etc.) will be characterized during baseline soil gas monitoring and may be further assessed at any point during the operational phase of the project, if needed.

Continuous and intermittent atmospheric monitoring data collected during the operational phase will be utilized to detect potential anomalous changes in surface conditions, which will be identified as an exceedance of a leakage detection threshold – to be defined after baseline background variability has been assessed (and with consideration of projected global increases in atmospheric carbon dioxide concentrations over time). If continuous and/or intermittent atmospheric monitoring data indicate a statistically significant departure between observed and baseline/seasonal parameter patterns in the surface air conditions, the anomaly will be further evaluated by one or more of the following responses: 1) detailed inspection and calibration of the EC tower and instrumentation; 2) detailed evaluation of potential effects of recent changes, if any, to the land use, vegetative conditions, local carbon dioxide sources, artificial penetrations, CCS-related operations, etc.; 3) supplemental testing of the atmosphere, targeting injection wells, monitoring wells, and other potential point sources; 4) testing of the soil gas to determine the presence of natural and/or anthropogenic carbon dioxide; and 5) if needed, attribution of the carbon dioxide detection to either natural variability or an anthropogenic source. If it is determined that the anomaly appears to be related to a potential carbon dioxide leak from the target reservoir,

additional testing of the USDW and the monitored basal Wilcox zone may be conducted. If further testing confirms potential leakage into the strata overlying the Confining Zone, then injection operations will cease and the procedures set out in the "*Emergency Remedial and Response Plan*" will be triggered.

The elements of the atmospheric monitoring program may be modified throughout the baseline and operational phases of the CCS project, as needed, as more data and information become available for the Site.

12.2 ECOSYSTEM STRESS MONITORING

Per UIC Program Site Characterization Guidance Subsection 2.3.11 and LCFS Protocol Subsections C.2.5(c)(3) and C.2.5(d)(1)(A), site characteristics including vegetation type and density in and around the storage complex should be defined during the baseline phase of the CCS project to establish the background vegetative conditions at the surface. Additionally, per LCFS Protocol Subsection C.4.3.2.2(f), ecosystem stress monitoring must be conducted in the form of annual vegetation surveys to measure potential stress resulting from elevated carbon dioxide in soil. As further discussed below, seasonal composite satellite images will be assessed retrospectively for three years prior to the end of baseline, and annually thereafter during operation. These evaluations will assess key metrics (e.g., biomass and vegetation health/stress) pre-injection and provide a mechanism for potential carbon dioxide release detection once the injection phase commences. To capture vegetation type and diversity metrics, a limited ground-based vegetation survey will be conducted during baseline to serve as a reference point if a future anomaly occurs, requiring ground-based verification. In addition to this temporal comparison of vegetative conditions, a spatial comparison will be conducted using surrounding pre-selected reference areas to account for other anomalous factors that may impact vegetation conditions within each assessment year.

12.2.1 Technology Selection

Satellite imagery will be used to evaluate vegetative conditions at the surface of the storage complex and its surrounding reference areas. This technology provides a mature, common, and frequently updated source of information for evaluating surface conditions. Satellite data will be

acquired from high-resolution and publicly available imaging platforms including Landsat 8 and 9 where data will be provided by the National Aeronautics and Space Administration (NASA) and the United Stated Geological Survey (USGS), and Sentinel-2 provided where data will be obtained from the European Space Agency (ESA). Qualitative and quantitative assessments of satellite imagery and derived indices will be performed to assess key vegetative health metrics such as plant biomass and health/stress. Qualitative assessments will consist of analyzing and comparing standard three-color composite images (e.g., natural color and false color) temporally, to baseline conditions, and spatially, to reference areas. Indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) will be utilized as quantitative indicators of vegetation conditions.

12.2.2 Reference Areas

Three reference areas surrounding the Area of Review will be used to compare vegetative conditions spatially per assessment timeframe (see Figures 3 and 4). These areas are representative of conditions outside the Area of Review and will thus serve as a comparison to vegetation not overlying the projected carbon dioxide plume. Three distinct reference areas, as opposed to one, were defined to enable statistically robust comparisons to be made between surrounding areas and the Area of Review and examine trends as a function of distance. Each reference area was selected based on characteristics that allow for direct comparisons to the Area of Review including size, EPA-defined Level III and Level IV Ecoregion designations, and land use characteristics. Each reference area will have a surface area approximately equal to the Area of Review (i.e., for a projected 1.5-mile radius plume, approximately 7 square miles). Reference areas will capture similar Ecoregions including Level III regions (the Mississippi Alluvial Plain and South-Central Plains) and Level IV regions (the Arkansas/Ouachita River Backswamps, Arkansas/Ouachita River Holocene Meander Belts, and Southern Tertiary Uplands) (see Figure 4). Finally, reference areas will capture similar land use characteristics as that of the Area of Review where land is primarily agricultural and/or undeveloped with few residential parcel properties (see Figure 3).

12.2.3 Monitoring and Assessment Methodology

Monitoring and assessment of ecological stress through vegetative conditions will take place at the Area of Review and the surrounding reference areas during the baseline and injection phases

of the CCS project. A ground-based vegetation survey, satellite imagery, and imagery data processing products will measure vegetative conditions through key metrics pre-injection and be capable of detecting any anomalous changes to vegetation during injection.

A baseline analysis will consist of one focused ground-based vegetation survey during the peak growing season of spring, focusing on the key metric of primary plant diversity and type. The survey will be conducted utilizing a "quadrant"-like approach, where similar vegetation and terrain areas will be characterized by their primary vegetation types in the Area of Review and surrounding reference areas, pending appropriate land access agreements. Additionally, as part of the baseline analysis, satellite imagery assessments will be conducted for three years of data retrospectively from the end of the baseline phase to capture both seasonal and annual variations of pre-injection vegetative conditions. During the operational phase, a similar satellite imagery analysis will take place on an annual basis. All available images will be processed into quarterly composite images, representative of each season. From these composite images, a variety of post-processing techniques will be used to develop various indices that can be used to quantify key vegetation-related attributes such as plant biomass and health/stress. Standard 3-color composite images (e.g., true color, false color) will support a qualitative analysis of vegetative conditions where significant anomalies in vegetation can be initially and quickly screened. Additionally, quantitative metrics will be calculated for satellite-derived images using standard algorithms developed by NASA, USGS, and ESA. NDVI, as well as a variety of other standard indices, will be used to quantify vegetation by greenness which provides information on plant density, biomass, and health.

Operation phase imagery and derived indices will be compared temporally to the three-year baseline satellite data, and spatially to surrounding reference areas in that same year. Since vegetative stress signals due to a carbon dioxide release have various potential confounding factors (e.g., droughts, floods, freezes, plant diseases, insect infestations, agricultural crop rotations, etc.), characterizing an anomaly attributed to injection will follow a tiered approach. As this tiered approach progresses, characterization of potential anomalies become more granular. If in an early tier no anomaly is detected, progression to the second and third tiers is not necessary. However, if moving through all three tiers is necessary and the anomaly cannot be attributed to an injection-related factor, further field verification may be conducted to assess the vegetative state of the Area

of Review. The tiered "Anomaly Characterization" approach is further described below.

1) Anomaly Characterization Tier 1
   - Qualitative assessment of standard 3-color composite images from current year to baseline conditions and surrounding reference areas.
   - Quantitative analysis of key satellite-derived indices such as NDVI and EVI from current assessment year to baseline conditions and surrounding reference areas.
2) Anomaly Characterization Tier 2 (if anomaly is detected in Tier 1 analysis)
   - Statistically evaluate ancillary data (e.g., climate indices, weather, local flux measurements) from various sources (e.g., local EC tower, the National Oceanic and Atmospheric Administration (NOAA), United States Department of Agriculture (USDA), United States Army Corp of Engineers (USACE), the National Weather Service, and United States Fish and Wildlife Service (USFWS)) to potentially attribute anomaly source to a non-injection related process.
   - Conduct an initial site area characterization analysis to determine if any non-injection-related factors not well-characterized by the available ancillary data have presented in the current assessment year. Such non-injection-related factors may include a unique crop rotation, significant land use changes, other anthropogenic factors, etc.
3) Anomaly Characterization Tier 3 (if anomaly in Tier 2 cannot be attributed to an ancillary source)
   - Retrospective analysis of the Area of Review and surrounding reference areas beyond that of the baseline assessment (e.g., 10-yr retrospective).
   - If Tier 1 anomalies are within range of historical variability (i.e., 10th-90th percentile), the anomalies will not be attributed to carbon dioxide release.

If further verification is required (i.e., all three tiers were assessed and no anomaly source was defined), then a ground-based site survey may be conducted to verify and validate the influence of CCS activities, if any, to this anomaly, pending appropriate land access agreements. Baseline limited vegetation survey data may be referenced to compare vegetation type and diversity metrics to the current assessment year.

The elements of the ecosystem stress monitoring program may be modified throughout the baseline and operational phases of the CCS project, as needed, as more data and information become

available for the Site.

12.3 SOIL GAS MONITORING

Soil gas data can be used to quantify the bulk chemical composition of gases in the near-surface soil layers and discern the source(s) of detected carbon dioxide as being sourced from either natural or anthropogenic sources (NETL, 2009). Per Standard 40 CFR §146.90(h) and LCFS Protocol Subsections C.2.5(c)&(d)&(e) and C.4.3.2.2(g), the requirement for continuous and/or intermittent soil gas monitoring is contingent upon one or more of the following conditions:

1) Results of the site-specific risk assessment, pursuant to LCFS Protocol Subsection C.2.2, and/or computational modeling, pursuant to LCFS Protocol Subsection C.2.4.1, indicate that "any property of the storage complex, groundwater, overburden, or surface projection of the storage complex" may "potentially be impacted by injection operations" (CARB, 2018).
2) Results of baseline or subsequent "deep subsurface or atmospheric monitoring suggests that atmospheric carbon dioxide leakage may occur or has occurred," (CARB, 2018) or that "movement of the carbon dioxide could endanger a USDW" (40 CFR §146.90(h)).

At this site, it is anticipated that soil gas monitoring will not be *required* during the baseline and operational phases of the project, due to the following site-specific conditions:

1) The project area is free of faulting at seismic resolution across either the Injection Zone or the Confining Zone.
2) No artificial penetrations (*e.g.*, oil and gas production or injection wells) within a 1.5-mile radius of the initial injection well penetrate the Tuscaloosa/Paluxy or Annona Sand Formations, with the exception of the following oil and gas wells:
    a. Well Serial No. 137738, which has a reported depth of 4,990 feet below ground level but is scheduled to be converted to a deep subsurface monitoring well for the Tuscaloosa/Paluxy and Annona Sand Injection Zones, and
    b. Well Serial No. 242591, which has a reported depth of 8,500 feet below ground level but is scheduled to have an adjacent deep subsurface monitoring well for the Lower Wilcox zone.

3) The presence of thick confining layers, such as the Midway Shale, Upper Selma Chalk, and Middle Chalk to Lower (Austin) Chalk (a combined thickness of approximately 1,600 feet), the Wash-Fred Limestone, the Cane River and Tallahatta Formations, and the lower confining layer, the Paluxy Shale, provide optimal quality of containment.
4) The saline sandstones and impermeable shales of the Wilcox Formation serve as a series of alternating buffer aquifers situated between the top of the Confining Zone and the lowermost USDW; as such, the Wilcox Formation serves as a "second line of defense" for protection of the USDWs. Moreover, monitoring of the basal Wilcox zone will provide for the early detection of a potential carbon dioxide leak.

It should be noted that several natural processes in the near surface soil layers (e.g., biological respiration, microbial oxidation of methane, etc.) can contribute to significant temporal variability in carbon dioxide concentrations. Background carbon dioxide concentrations and isotopic compositions in soils are largely "dependent on exchange with the atmosphere, organic matter decay, uptake by plants, root respiration, deep degassing, release from groundwater due to depressurization, and microbial activities (Oldenburg and Lewicki, 2004)" (EPA, 2013b). Therefore, some component of soil gas monitoring during the baseline phase of the project is useful to (i) define the baseline molecular and isotopic compositions of the shallow soil gas, and (ii) characterize natural background variability, including seasonal and diurnal trends. The results of the baseline soil gas monitoring may then be used for future reference and comparison to operational soil gas monitoring, if needed, to assist in the detection, validation, and quantification of potential carbon dioxide leakage. To this end, a limited intermittent soil gas monitoring program will be conducted during baseline monitoring operations utilizing permanent soil gas probes as an active [whole air] sample collection method.

12.3.1 Monitoring Location and Frequency

Permanent subsurface soil gas probes will be installed at 12 to 15 representative locations throughout the surface projection of the Area of Review. The baseline soil gas monitoring network will depend on appropriate land access agreements, and will include, at a minimum, three probe sites in the vicinity of the initial injection well site, and one probe site at each of the remaining four proposed injection well sites, the two Tuscaloosa/Paluxy/Annona Sand monitoring wells, and the single basal Wilcox monitoring well. One or more probes may also be installed within the

ecosystem stress monitoring reference areas. The remaining locations of the soil gas probe sites will be determined as more data and information become available for the site during the baseline and operational phases of the project. It is anticipated that the baseline soil gas monitoring network will be utilized during the operational phase as well, as needed.

Soil gas samples will be collected manually from the soil gas probe sites on a monthly and quarterly basis during the 1- to 2-year baseline and estimated 20-year operational phases, respectively. During the post-injection site care phase, supplemental soil gas monitoring may be considered as part of a post-injection site care leak detection strategy, based upon final approval of the demonstration of plume stability.

12.3.2 Soil Gas Probe Construction Procedures

Soil gas probe sites will be installed to a depth of approximately 10 feet below ground level, dependent upon the depth to shallow groundwater and presence of low-permeability (e.g., clay) zones, utilizing traditional direct-push or hand-auger drilling technologies and equipment. During borehole advancement, a continuous soil core will be collected and logged in accordance with Unified Soil Classification System (USCS) guidelines to determine soil type. Additionally, soil samples will be collected in general accordance with EPA Method LSASDPROC-300-R4 (EPA, 2020a) for the laboratory analysis of soil moisture and salinity according to Standard Methods (SM) 2540G and 2520B, respectively, and for total organic carbon (TOC) content according to the Walkley Black 9060A method. Table 21 below identifies the parameters to be monitored and the analytical methods the Louisiana Green Fuels, Port of Columbia Facility will use for the soil samples.

Soil gas probes will be constructed in general accordance with operating procedures set forth in EPA Method LSASDPROC-307-R4 (EPA, 2020b), and will consist of stainless-steel vapor implant points attached securely to 1/8th-inch Nylaflow® tubing and lowered to the bottom of the borehole. A sand pack using U.S. mesh interval 20/40 sand will be installed to approximately 6-inches above the vapor implant point. The remainder of the borehole will be backfilled with granular bentonite to the ground surface and hydrated to create an annular seal. The upper 1-foot of tubing will be encased within 1-inch diameter, schedule 40 polyvinyl chloride (PVC) pipe at the surface. The tubing will be threaded through a drilled, tight-fitting PVC slip cap and sealed

from atmospheric air utilizing a stainless-steal Swagelok® capping fitting. The tubing at the surface will be concealed within a 6-inch steel, flush mount manway, individually installed with a concrete pad, for protection and easy accessibility. Detailed soil gas probe location and construction information will be recorded at each site.

12.3.3 Soil Gas Sampling and Testing Methods

Soil gas sampling will be conducted in general accordance with operating procedures set forth in EPA Method LSASDPROC-307-R4 (EPA, 2020b). During sample collection, a vacuum will be applied to the tubing on the surface to first purge the full length of the tubing, and second collect a soil gas sample in a 0.3-L IsoBag® Gas Bag using 60 mL gas-tight syringes, equipped with a 3-way valves. During soil gas sampling, a leakage test will be conducted by releasing helium gas as a tracer gas within a shroud over each soil gas sampling site.

Soil gas samples will be submitted for the laboratory analysis of various geochemical methods, including natural tracers (isotopes of carbon [C]). Table 21 below identifies the parameters to be monitored and the analytical methods the Louisiana Green Fuels, Port of Columbia Facility will use for the soil gas samples.

Table 21: Summary of analytical parameters for soil and soil gas samples

Parameter	Analytical Method
Surface Soil	
Percent Moisture	ASTM D2216
Fraction Organic Carbon	ASTM D2974-87
Salinity	Total Soluble Salts (TSS)
Soil Gas	
CO_2, CH_4, N_2, O_2	Gas chromatography
C1-C5 hydrocarbons	Gas chromatography
Helium	Gas chromatography
$\delta^{13}C$ of CO_2 and CH_4	Gas chromatography/ combustion/ isotope ratio mass spectrometry
C^{14} of CO_2 and CH_4	Accelerated mass spectrometry
δD of CH_4	Gas chromatography/ combustion/ isotope ratio mass spectrometry

Following baseline monitoring, protocols and thresholds for carbon dioxide leak detection will be developed for the operational phase of the project, which will include process-based methods utilizing gas ratios of CO_2, O_2, N_2, and CH_4 and isotopic compositions of CO_2 and CH_4.

An anomalous detection of carbon dioxide above background levels in soil gas "does not necessarily demonstrate that USDWs have been endangered, but it may indicate that a leakage pathway or conduit exists" (EPA, 2013b). Therefore, if it is determined that a statistically significant departure between observed and baseline/ seasonal parameter patterns appears to be related to a potential carbon dioxide leak from the target reservoir, additional testing of the atmosphere, USDW, and the basal Wilcox zone may be conducted. If further testing confirms potential leakage into the strata overlying the Confining Zone, then injection operations will cease and the procedures set out in the *"Emergency Remedial and Response Plan"* will be triggered.

The elements of the soil gas monitoring program may be modified throughout the baseline and operational phases of the project, as needed, as more data and information become available for the Site.

12.3.4 Analysis Procedures and Chain of Custody

Soil and soil gas samples will be collected into the appropriate lab-supplied, method-specific sample containers, properly preserved (as needed), and shipped within 24 hours of collection for analysis by third party laboratories accredited by the Louisiana Department of Environmental Quality (https://internet.deq.louisiana.gov/portal/divisions/lelap/accredited-laboratories) using standardized procedures. Detection limits will be dependent on equipment facilitated for the analytical methods by the selected qualified vendor and meet the minimum levels set forth in Appendix 1.

The sample chain-of-custody procedures will be dependent on vendor selection as they will assume the custody of the samples. The procedures will document and track the sample transfer to laboratory, to the analyst, to testing, to storage, and to disposal (at a minimum). A sample chain-of-custody procedure-s is illustrated in the attached QASP (Appendix 1).

The initial parameters identified in Table 21 may be revised and include additional components for testing dependent on the initial geochemical evaluation.

13.0 SEISMICITY MONITORING

Natural seismicity in the project area is exceedingly low, with no recorded earthquakes in either Caldwell Parish or the immediately adjacent parishes (https://earthquake.usgs.gov/earthquakes/search/). The closest recorded earthquakes are located more than 125 kilometers away from the Port of Columbia Facility, near the Arkansas-Louisiana State Line.

Induced seismicity risk is also low because of high transmissivity of the Tuscaloosa/Paluxy sands and lack of brittle rocks within, above, or below the Tuscaloosa/Paluxy and/or Annona Injection Zones. Previous measurements of induced seismicity in Department of Energy supported research projects along the Gulf Coast (the Mississippi Cranfield Project, for example), have not detected induced seismicity events resulting from the injection of large volumes of carbon dioxide.

Therefore, the regional and local seismicity will be monitored annually for any change in frequency. Only if a change in frequency occurs, will additional site-specific monitoring of local events be undertaken by the Port of Columbia Facility.

14.0 APPENDIX: QUALITY ASSURANCE AND SURVEILLANCE PLAN

The QASP is submitted as Appendix 1 to this Testing and Monitoring Plan.

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FIGURES

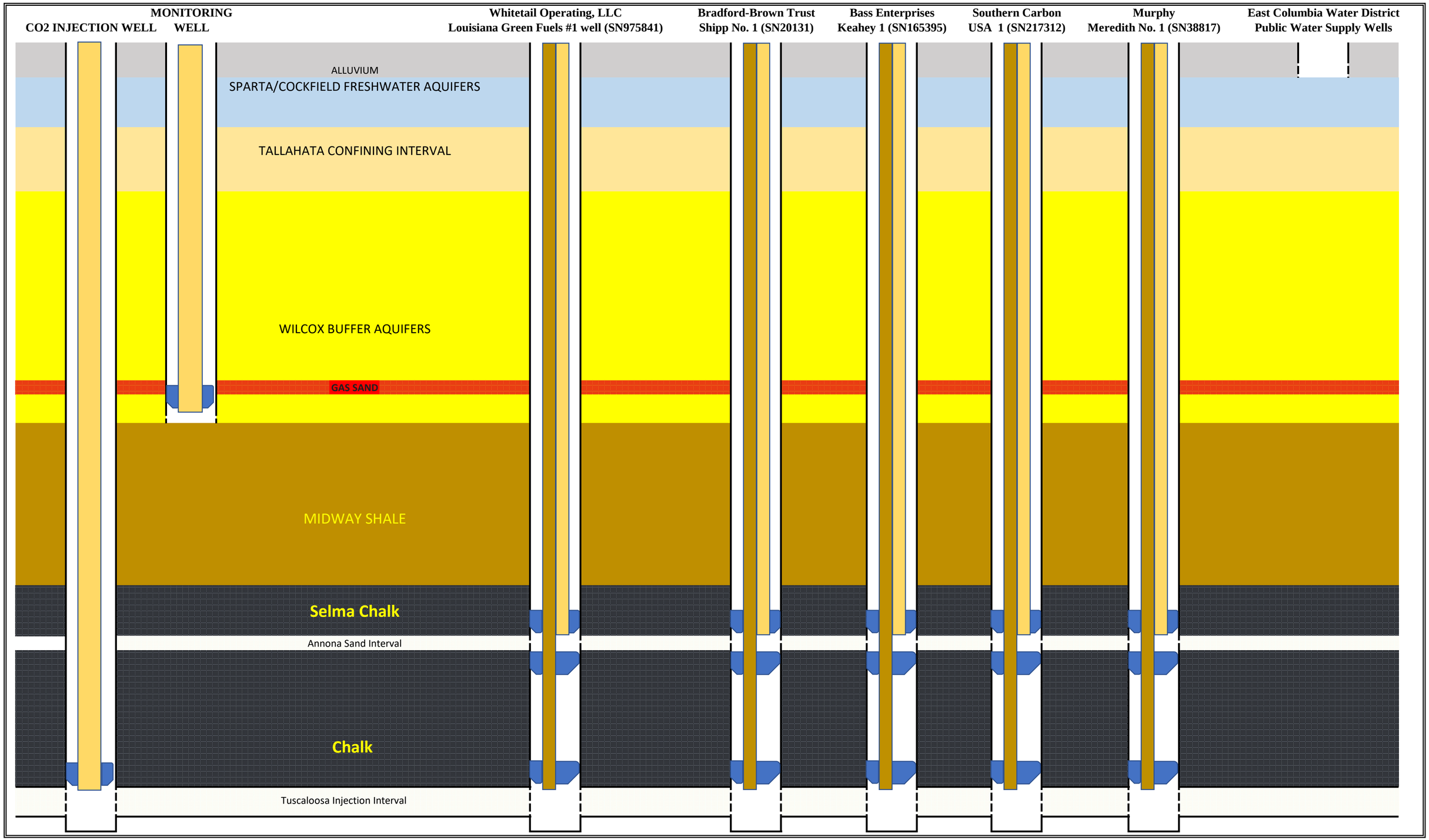
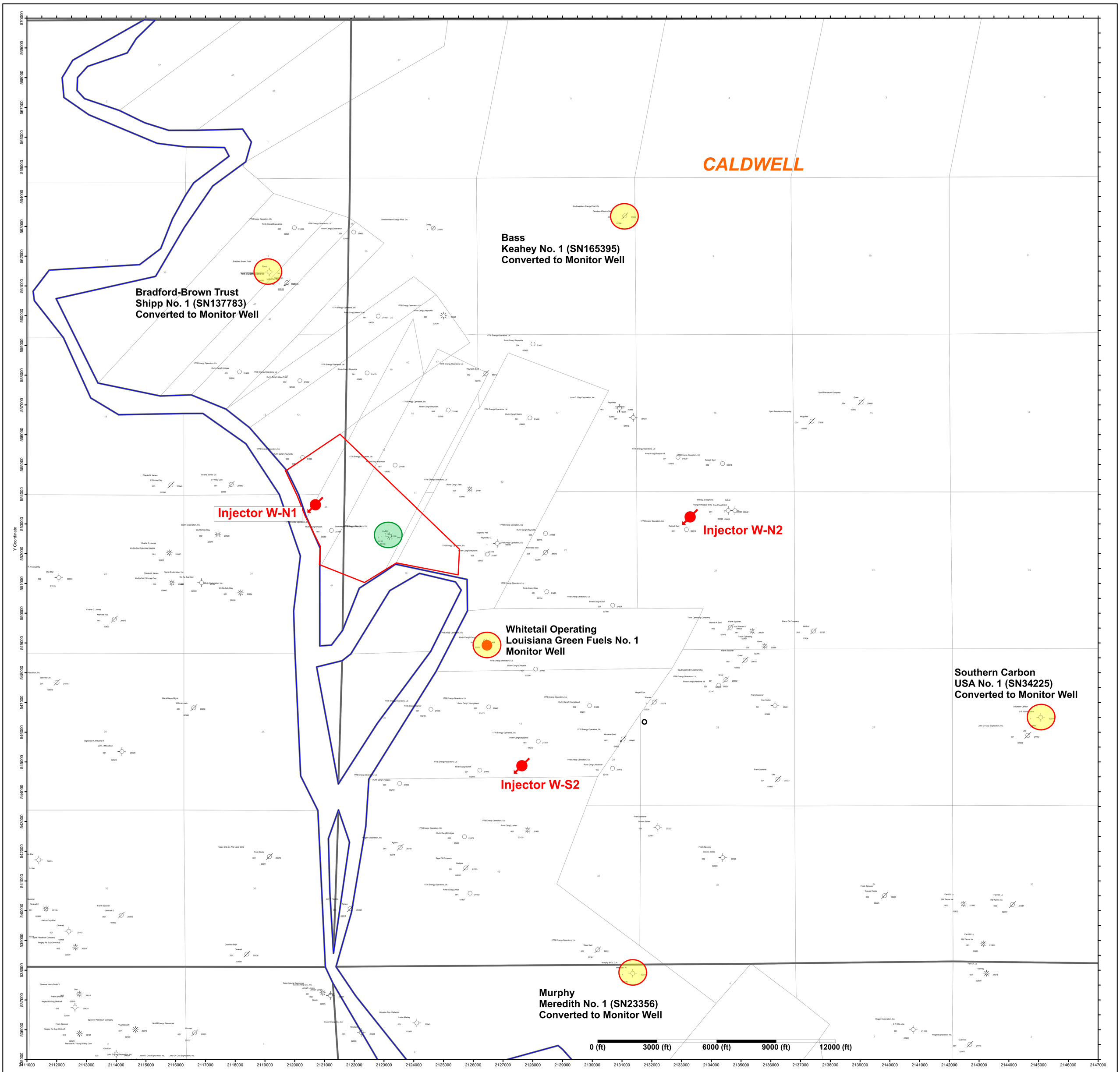
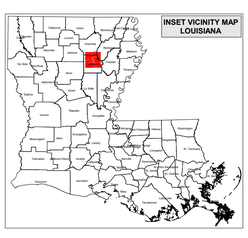


Figure 1 - Proposed Louisiana Green Fuels Port of Columbia Facility Monitoring Schematic Illustration





LEGEND:

- Location (Permit)
- Abandoned Location
- Gas Well
- Oil Well
- Oil & Gas Well
- Dry Hole (No Shows)
- Injection Well
- Suspended
- Plugged Gas Well
- Plugged Oil Well
- Plugged Oil & Gas
- Dry Hole (Oil Shows)
- Dry Hole w (Gas Shows)
- Dry Hole (Oil & Gas Shows)

Tuscaloosa & Annona Sand Monitor Well

Basal Wilcox Monitor Well

Scale: 1" = 3000'
Scale Ratio: 1:36,000
Note: NAD_1927_StatePlane_Louisiana_North_FIPS_1701 (US FT)

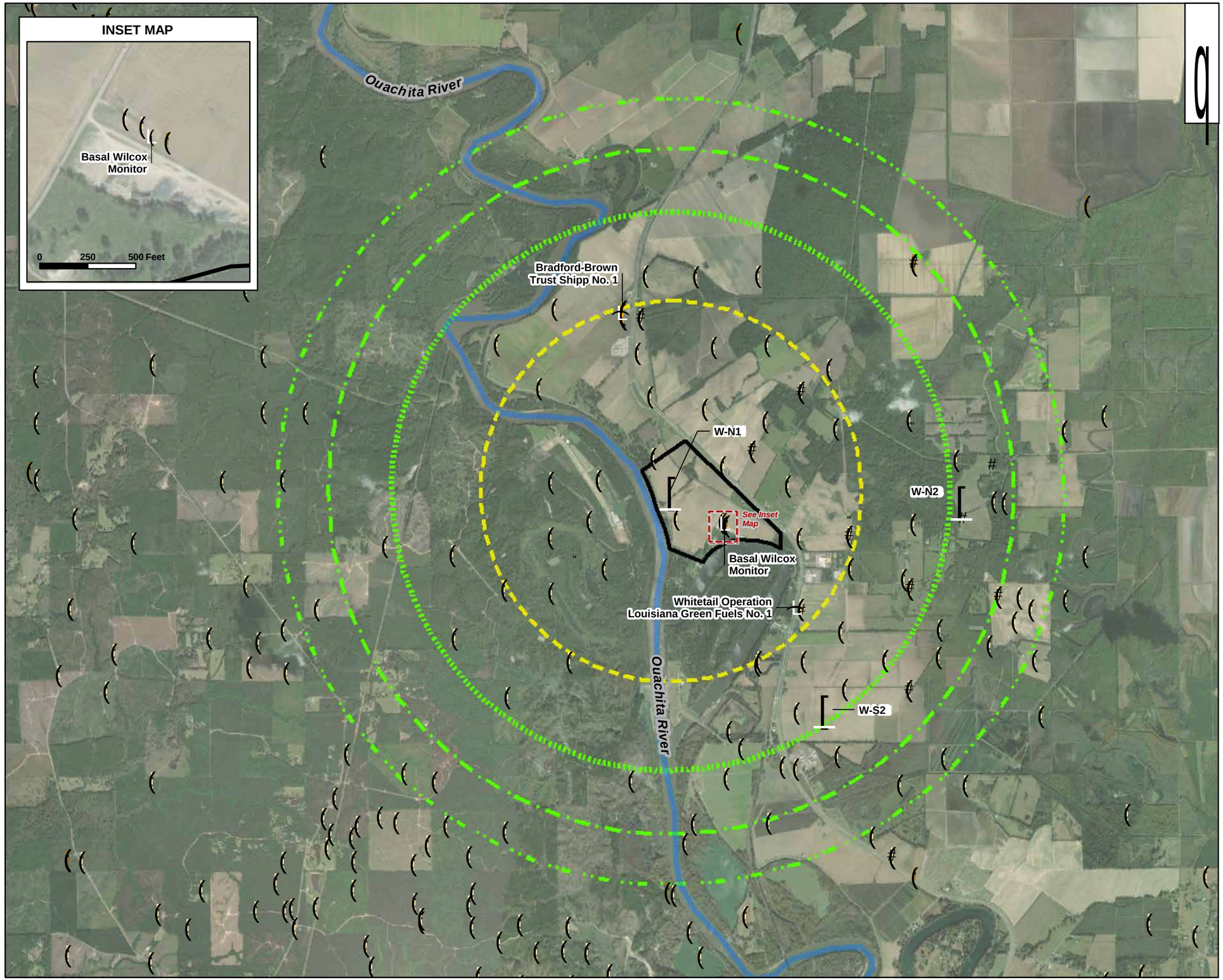
STRATEGIC BIOFUELS

Strategic BioFuels
Caldwell Parish LA

Figure 2 Monitoring Well Network Layout

by: ESSJ & DJC (GKS)	Scale: See SCALEBAR	Date: January 2023

GEOSTOCK SANDIA ENTREPOSE



LEGEND

- Proposed CO_2 Injection Well
- Proposed Basal Wilcox Monitoring Well
- Proposed Tuscaloosa & Annona Sand Monitoring Well
- Brine Injection Well
- Oil and Gas Well
- Repotted well depth = 4,000 ft bgs
- Repotted well depth between 4,000 - 5,000 ft bgs
- Repotted well depth = 5,000 ft bgs
- Port of Columbia Site Boundary
- Area of Review (1.5-mile radius)
- Reference Area # 1 (2.2-mile radius)
- Reference Area # 2 (2.7-mile radius)
- Reference Area # 3 (3.1-mile radius)

PRELIMINARY DRAFT

Notes

1. Hatch color coding for artificial penetrations include Oil and Gas and Brine Injection Wells.
2. Area of Review and Reference Area radius distance are from INJ #1.
3. Background Image: ESRI World Image - 1m Color Infrared NAIP Image. Source: Esri, Digital Globe, GeoEye, et al. Approximate Google Earth date 5/2021.

Feet
0 2,000 4,000

Projected Coordinate System
Datum: NAD 1927
STP: Louisiana North, FIPS 1701 (ft)

GSI ENVIRONMENTAL

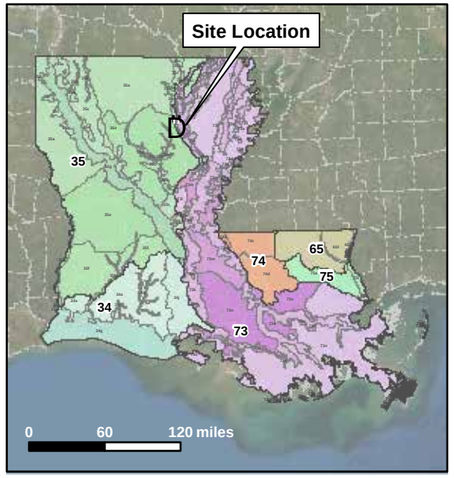
SITE LAYOUT: NEARBY ARTIFICIAL PENETRATIONS

Louisiana Green Fuels, Strategic BioFuels LLC
Port of Columbia Site, Caldwell Parish, Louisiana

GSI Job No. 6236	Drawn By: CDM
Issued: DRAFT	Chkd By: JA
Map ID: 001_01	Appv'd By:

FIGURE 3

W

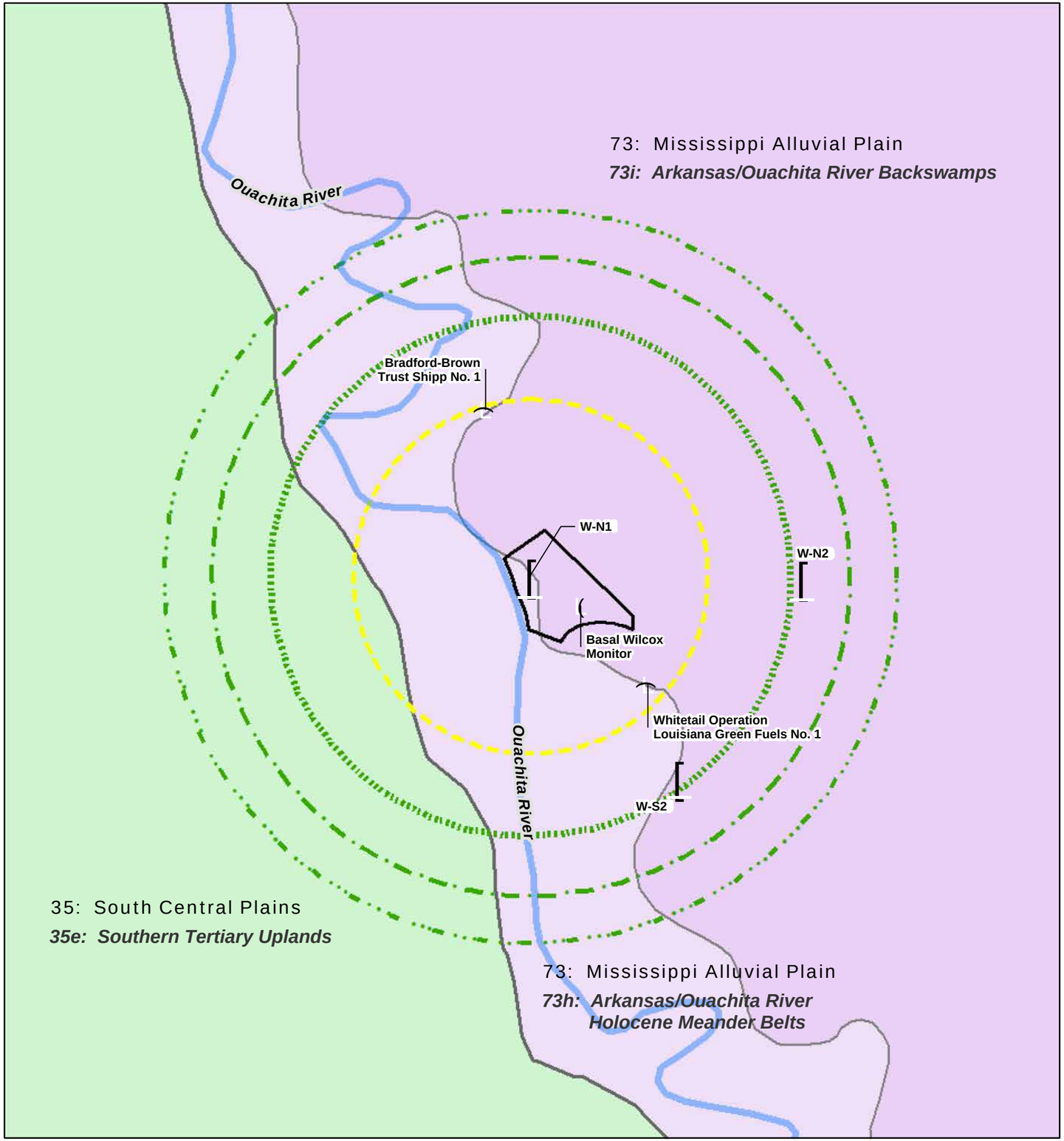


Level III Ecoregion

- 34 Western Gulf Coastal Plain
- 35 South Central Plains
- 65 Southeastern Plains
- 73 Mississippi Alluvial Plain
- 74 Mississippi Valley Loess Plains
- 75 Southern Coastal Plain

Level IV Ecoregion

- 34a Northern Humid Gulf Coastal Prairies
- 34c Flood plains and Low Terraces
- 34g Texas-Louisiana Coastal Marshes
- 34j Lafayette Loess Plains
- 35a Tertiary Uplands
- 35b Flood plains and Low Terraces
- 35c Pleistocene Fluvial Terraces
- 35e Southern Tertiary Uplands
- 35f Flatwoods
- 35g Red River Bottomlands
- 65f Southern Pine Plains and Hills
- 65p Southeastern Flood plains and Low Terraces
- 73a Northern Holocene Meandered Belts
- 73d Northern Backswamps
- 73h Arkansas/Ouachita River Holocene Meandered Belts
- 73i Arkansas/Ouachita River Backswamps
- 73j Macon Ridge
- 73k Southern Holocene Meandered Belts
- 73l Southern Pleistocene Valley Trains
- 73m Southern Backswamps
- 73n Inland Swamps
- 73o Deltaic Coastal Marsh sand Barrier Islands
- 74a Bluff Hills
- 74c Southern Rolling Plains
- 74d Baton Rouge Terrace
- 75a Gulf Coast Flatwoods
- 75i Flood plains and Low Terraces
- 75k Gulf Barrier Island sand Coastal Marshes



LEGEND

- Proposed CO_2 Injection Well
- Proposed Basal Wilcox Monitoring Well
- Proposed Tuscaloosa & Annona Sand Monitoring Well
- Port of Columbia Site Boundary
- Area of Review (1.5-mile radius)
- Reference Area # 1 (2.2-mile radius)
- Reference Area # 2 (2.7-mile radius)
- Reference Area # 3 (3.1-mile radius)

PRELIMINARY DRAFT

Note

1. Area of Review and Reference Area radius distances are from INJ #1.
2. Background Imagery: ESRI World Imagery – 1m Color InfraRed NAIP Imagery. Source: Esri, DigitalGlobe, GeoEye, et al. Approximate Google Earth date 5/2021.

Feet
0 2,500 5,000

Projected Coordinate System
Datum: NAD 1927
STP: Louisiana North, FIPS 1701 (ft)

GSI ENVIRONMENTAL

SITE LAYOUT: LOCAL ECOREGION CLASSIFICATIONS

Louisiana Green Fuels, Strategic BioFuels LLC
Port of Columbia Site, Caldwell Parish, Louisiana

GSI Job No. 6236	Drawn By: CDM
Issued: DRAFT	Chk'd By: JA
Map ID: 001_02	Appv'd By:

FIGURE 4

Appendix 1 : Quality Assurance and Surveillance Plan

CLASS VI INJECTION WELL: APPENDIX 1 - QUALITY ASSURANCE AND SURVELLIANCE PLAN

Appendix to the Testing and Monitoring Plan - 40 CFR 146.90 & LCFS Protocol Subsection C.4.1(a)

STRATEGIC BIOFUELS
LOUISIANA GREEN FUELS PORT OF COLUMBIA FACILITY

Prepared By:
GEOSTOCK SANDIA, LLC

Revision No. 0
February 2023

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TITLE AND APPROVAL SHEET

This Quality Assurance and Surveillance Plan (QASP) is approved for use and implementation at Louisiana Green Fuels – Port of Columbia Facility. The signatures below denote the approval of this document and intent to abide by the procedures outlined within it.

Add lines as needed to include all appropriate staff.

Signature [INSERT TYPED NAME] [INSERT TITLE]	Date
Signature [INSERT TYPED NAME] [INSERT TITLE]	Date
Signature [INSERT TYPED NAME] [INSERT TITLE]	Date

DISTRIBUTION LIST

The following project participants will receive the completed Quality Assurance and Surveillance Plan (QASP) and all future updates for the duration of the project.

Distribution:

Add lines as needed to include all appropriate staff.

[INSERT TYPED NAME] [INSERT TITLE]	Date
[INSERT TYPED NAME] [INSERT TITLE]	Date
[INSERT TYPED NAME] [INSERT TITLE]	Date

A. PROJECT MANAGEMENT

A.1. Project/Task Organization

A.1.a/b. Key Individuals and Responsibilities

The Louisiana Green Fuels project is led by Strategic Biofuels and includes participation from several subcontractors. The Testing and Monitoring activities responsibilities will be shared between Louisiana Green Fuels and their designated subcontractors, and conducted in the following subcategories:

I) Sampling and analysis of the carbon dioxide stream, required at a frequency that will yield information on the chemical composition and physical characteristics of the injectate [40 CFR 146.90(a)].

II) Monitoring of operational parameters (injection pressure, rate, and volume, pressure on the annulus, and annulus fluid volume) through the use of continuous recording devices [40 CFR 146.90(b)].

III) Corrosion monitoring of injection well materials, required on a quarterly basis [40 CFR 146.90(c)].

IV) Monitoring of ground water quality and geochemical changes above the confining zone(s), at a site-specific frequency and spatial distribution [40 CFR 146.90(d)].

V) External Mechanical Integrity Testing (MIT), at least once per year [40 CFR 146.90(e)].

VI) Pressure fall-off testing, at least once every five years [40 CFR 146.90(f)].

VII) Testing and monitoring to track the extent of the carbon dioxide plume and the presence or absence of elevated pressure (e.g., pressure front) [40 CFR 146.90(g)].

VIII) Continuous and intermittent surface air, and intermittent soil gas monitoring [40 CFR 146.90(h); LAC Title 43 Part XVII §3625(A)(8) (State of Louisiana); CARB LCFS Subsections C.2.5 and C.4.3.2.2; USEPA, 2013a;b].

IX) Baseline soil sampling for site characterization [CARB LCFS Subsection C.4.3.2.2; USEPA, 2013a, Subsection 2.3.11].

X) Ecosystem stress monitoring in the form of vegetation surveys [CARB LCFS Subsections C.2.5 and C.4.3.2.2; USEPA, 2013a, Subsection 2.3.11]

XI) Any additional monitoring that the UIC Program Director determines to be necessary to support, upgrade, and improve computational modeling of the AoR and to determine compliance with standards under 40 CFR 144.12 [40 CFR 146.90(i)].

A.1.c. Independence from Project QA Manager and Data Gathering

The majority of the physical samples collected and data gathered as part of the Monitoring, Verification, and Accounting (MVA) program will be analyzed, processed, or witnessed by third parties independent and outside of the project management structure.

A.1.d. QA Project Plan Responsibility

Louisiana Green Fuels is responsible for developing, maintaining and distributing an official, approved Quality Assurance project plan. Louisiana Green Fuels will periodically (no less than once every five years) (CARB, 2018, p. 79) review the Quality Assurance and Surveillance Plan (QASP) and consult with the U.S. Environmental Protection Agency (USEPA) and the California Air Resources Board (CARB) if/when changes to the plan are warranted.

A.1.e. Organizational Chart for Key Project Personnel

Figure 1 shows the organization structure of the project. Louisiana Green Fuels will provide to the Underground Injection Control (UIC) Program Director a contact list of individuals fulfilling these roles.

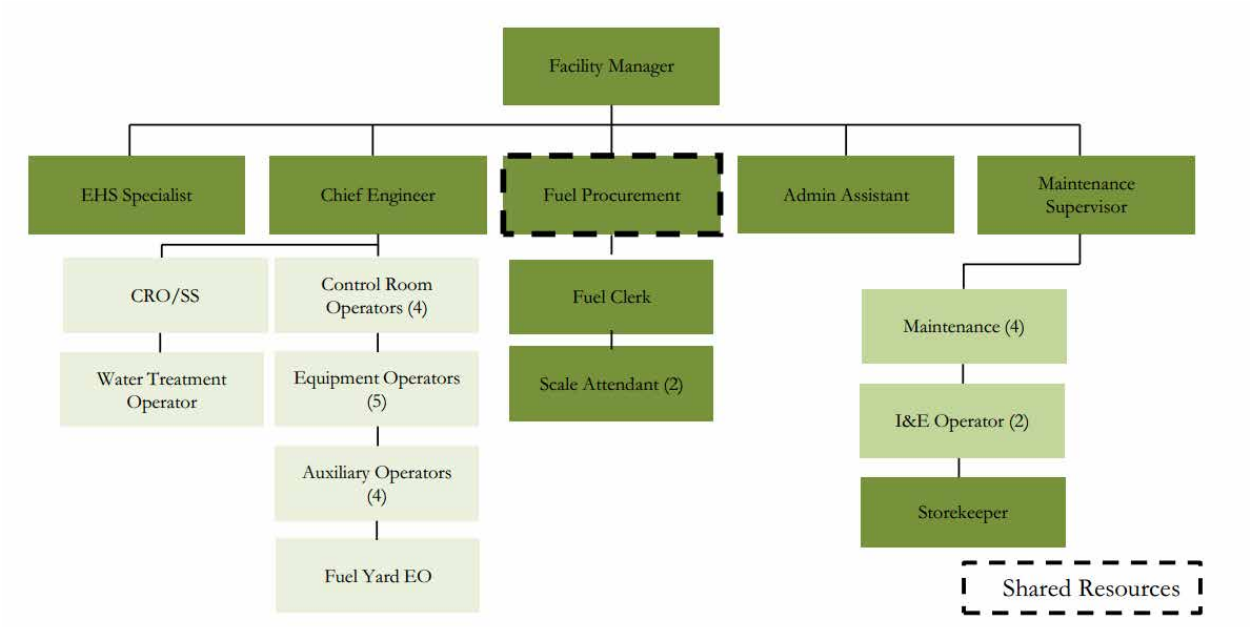

Figure 1. Louisiana Green Fuels Organization.

A.2. Problem Definition/Background

A.2.a. Reasoning

This QASP is aimed at supporting the Testing and Monitoring (T&M) plan included in the Class VI permit request submitted by Louisiana Green Fuels for the geological sequestration of the carbon dioxide produced at their Louisiana Green Fuels Port of Columbia Facility in Caldwell Parish, Louisiana. The T&M plan addresses the requirements of the Class VI Rule specifications and the Carbon Capture and Sequestration (CCS) Protocol under the USEPA and CARB Low-Carbon Fuel Standard (LCFS) (Subsections C.2.5 and C.4.3.2.2; CARB, 2018), respectively, and employs best practices developed in similar CO_2 injection and storage projects.

The primary goal of the Monitoring, Verification, and Accounting (MVA) program is to demonstrate that project activities are protective of human health and the environment. This QASP was developed to help achieve this goal and ensure the quality standards of the Testing and Monitoring program meet the requirements of the U.S. Environmental Protection Agency's (USEPA) Underground Injection Control (UIC) program for Class VI wells and the California CCS LCFS protocol. A robust risk-based MVA program has been developed for the Louisiana

Green Fuels project based on the knowledge and experience gained through the analysis of the comprehensive dataset acquired in the stratigraphic test well and the preparation of the permit application modules which assure with a high level of confidence that the storage units will be capable to accept and permanently retain the injectate.

The Louisiana Green Fuels project's MVA program has operational monitoring, verification, and environmental monitoring components. Operational monitoring will be used to ensure safety with all procedures associated with fluid injection and monitor the response of storage units and the movement of the CO_2 plume. Key monitoring parameters include the pressure of injection well tubing and annulus, storage units, above seal strata, and lowermost underground source of drinking water (USDW) reservoir. Other monitoring parameters include injection rate, total mass and volume injected, injection well temperature profile, and passive seismic. The verification component will provide information to evaluate if leakage of CO_2 through the caprock is occurring. This includes pulse neutron logging, pressure, and temperature monitoring. The environmental monitoring component will determine if the injectate is being released into the shallow subsurface or biosphere. This monitoring includes pulse neutron logging, ground water, surface air, soil gas, and ecosystem stress monitoring.

A.2.b. Reasons for Initiating the Project

The T&M plan goals are to comply with the Class VI Rule and CARB LCFS protocols and document via targeted data collection that the prediction made during subsurface characterization and modeling are correct and that the CO_2 and brine solutions will remain in the Injection zone, isolated from the USDW, near-surface and atmosphere.

A.2.c. Regulatory Information, Applicable Criteria, Action Limits

The Class VI Rule and CARB LCFS Protocol require owners or operators of Class VI injection wells to perform several types of activities during the lifetime of the project in order to ensure that each injection well maintains its mechanical integrity, that fluid migration and the extent of pressure elevation are within the limits described in the permit application, and that underground sources of drinking water (USDWs) are not endangered. These monitoring activities include

Mechanical Integrity Tests (MITs), injection well testing during operations, monitoring of ground water quality above the Confining zone, tracking of the CO_2 plume and associated pressure front, surface air, soil gas, and ecosystem stress monitoring. This document details the measurements that will be taken as well as the steps to ensure that data quality is such that data can be used with confidence in making decisions during the life of the project.

A.3. Project/Task Description

A.3.a/b. Summary of Work to be Performed

Table 1 describes the testing and monitoring tasks, including locations, analytical techniques, methods, responsible parties, and purposes. Note that the testing frequency is provided in the T&M plan. Tables 2 and 3 summarize the instrumentation and geophysical surveys, respectively.

Table 1. Summary of Testing and Monitoring.

Activity	Location(s)	Method	Analytical Technique	Lab/Custody	Purpose
Carbon dioxide stream analysis	Flowline	High-pressure vessel	Standard laboratory gas analyses	lab accredited by the LDEQ	Monitor injectate quality
Injection rate/volume	Injection well(s) – After compressor	Flow meter	Direct continuous measurement	N/A	Monitor rate/volume
Injection pressure	Injection well(s) – Wellhead	Pressure gauge	Direct continuous measurement	N/A	Monitor injection pressure at surface
Injection temperature	Injection well(s) – Wellhead	Temperature gauge	Direct continuous measurement	N/A	Monitor injection temperature at surface
Annular pressure	Injection well(s) – Wellhead	Pressure gauge	Direct continuous measurement	N/A	Monitor annular pressure at surface
In Zone Downhole pressure/temperature	Injection well(s)	Wireline downhole pressure/temperature gauge	Direct continuous measurement	N/A	Monitor reservoir response
Corrosion monitoring	Flowline – After compressor	Weight loss in holder, and observation	ASTM G1-03 and/or NACE Standard RP0775-2005 Item No. 21017	3rd Party	Monitor corrosion risk
Distributed Temperature Sensing (DTS) fiber optics[1]	Injection well(s)	Fiber optic cable	Direct continuous measurement	3rd Party	Monitor wellbore integrity

Activity	Location(s)	Method	Analytical Technique	Lab/Custody	Purpose
Mechanical integrity (casing)	Injection well(s)	Various	40 CFR §146.87 (a)(4) and 40 CFR §146.89 (c)(2)	3rd Party	Monitor wellbore integrity and detect potential leakage through casing
Mechanical integrity (cement)	Injection well(s)	Wireline cement evaluation logging	Provided by Vendor	3rd Party	Monitor wellbore integrity and detect potential leakage through cement
Pressure fall-off testing	Injection well(s)	EPA Region 6 UIC Pressure Fall-off Testing Guideline – Third Revision (August 8, 2002)	EPA Region 6 UIC Pressure Fall-off Testing Guideline – Third Revision (August 8, 2002)	3rd Party	Monitor wellbore integrity and assess injectivity
Wireline logging – Pulsed Neutron Logging	Injection well(s)	Wireline formation evaluation logging	Provided by vendor	3rd Party	Identify zones that are accepting CO_2
In-zone pressure monitoring – Tuscaloosa	2 selected wells	Downhole pressure/temperature gauge	Direct continuous measurement	N/A	Monitor in-zone pressure/temperature
Above-Injection Zone pressure monitoring (AZMI) – Annona Sand	2 selected wells	Downhole pressure/temperature gauge	Direct continuous measurement	N/A	Monitor above-zone pressure within Sequestration Complex

Activity	Location(s)	Method	Analytical Technique	Lab/Custody	Purpose
Adaptive Sampling-Annona	2 selected wells	Swab or other method	Chemical/Physical Analyses	Lab accredited by the LDEQ	Monitor Sequestration Complex
Above Confining Zone pressure monitoring (ACZMI) – Wilcox	1 onsite monitor well	Downhole pressure/temperature gauge	Direct continuous measurement	N/A	Monitor pressure above Confining Zone
Sampling-Wilcox	1 onsite monitor well	Swab or other method	Chemical/Physical Analyses	Lab accredited by the LDEQ	Monitor Above Sequestration Complex
Sampling-Public Water Supply	East Columbia Water District	Pumping or other method	Chemical/Physical Analyses	Lab accredited by the LDEQ	Monitor groundwater
CO_2 plume tracking	Injection & Monitoring wells	Time-lapseVertical Seismic Profiles (VSP) or other method	Provided by vendor	3rd Party	Track CO_2 plume size and monitor changes in subsurface
Atmospheric monitoring	1 onsite tower and selected sites in AoR	Surface air sampling and net CO_2 flux calculation	Direct measurement	3rd Party	Monitor environmental changes
Ecosystem Stress monitoring	AoR and Reference Areas	Vegetation surveys	Satellite imagery analysis	3rd Party	Monitoring environmental changes

Activity	Location(s)	Method	Analytical Technique	Lab/Custody	Purpose
Soil Gas monitoring	12-15 discrete points in AoR	Soil gas sampling	Standard laboratory analyses (gas chromatography and mass spectrometry)	Istotech Laboratories and Beta Analytics	Monitoring environmental changes
Soil Characterization	12-15 discrete points in the AoR	Soil Sampling	Standard laboratory analyses	Eurofins Houston	Establish site soil characteristics

[1] If deployed

Table 2. Instrumentation Summary.

Monitoring Location	Instrument Type	Monitoring Target (Formation or Other)	Data Collection Location(s)	Explanation
CO_2 facility	High-pressure vessel	Surface/Flowline	Tap on Flowline	Monitor injectate quality
	Flow meter	Surface/Flowline	Flowline	Monitor injectate rate/volume
Injection well(s)	Pressure/temperature gauge (on tubing)	Wellhead	Wellhead tap	Monitor injection conditions; safety and compliance
	Pressure gauge (on annulus)	Wellhead	Wellhead tap	Monitor injection conditions; safety and compliance
	Wireline downhole pressure/temperature gauge	Annona & Tuscaloosa Injection Zones	Perforations	Monitor downhole conditions; safety and compliance
	Weight loss coupons in holder	Surface/Flowline	ASTM G1-03 and/or NACE Standard RP0775-2005 Item No 21017	Monitor corrosion
	Distributed Temperature Sensing (DTS) fiber-optic cable	Whole formation section down to Confining Zone	Dedicated server (VSP array)	Monitor wellbore integrity

Monitoring Location	Instrument Type	Monitoring Target (Formation or Other)	Data Collection Location(s)	Explanation
	Various	Whole formation section	40 CFR §146.87 (a)(4) and 40 CFR §146.89 (c)(2)	Monitor wellbore integrity
	Wireline cement evaluation logging	Whole formation section	Casing	Monitor wellbore integrity
	EPA Region 6 UIC Pressure Fall-off Testing Guideline – Third Revision (August 8, 2002)	Annona, Upper Tuscaloosa, and Lower Tuscaloosa injection zones	EPA Region 6 UIC Pressure Fall-off Testing Guideline – Third Revision (August 8, 2002)	Monitor wellbore integrity and assess injectivity
	Wireline formation evaluation logging tools	Whole formation section	Open Hole	Track formation property changes
	Distributed Acoustic Sensing (DAS) fiber-optic cable[1]	Whole formation section	Dedicated server (VSP array)	CO_2 plume tracking and well integrity
In-zone monitoring wells	Pressure/temperature gauge (on tubing)	Tuscaloosa Formation	Wellhead	Safety and compliance
	Downhole pressure/temperature gauge	Tuscaloosa Injection Zones	Perforations	Monitor downhole conditions of pressure/temperature in the Injection Zone

Monitoring Location	Instrument Type	Monitoring Target (Formation or Other)	Data Collection Location(s)	Explanation
Above-zone monitoring wells (AZMI) -Annona Sand	Pressure/temperature gauge (on tubing)	Annona Formation	Wellhead	Safety and compliance
	Downhole pressure/temperature gauge	Annona Sand	Perforations	Verify that no fluid is escaping from the Tuscaloosa Injection Zone
Above-Confining Zone monitoring wells (ACZMI) - Wilcox Sand	Pressure/temperature gauge (on tubing)	Basal Wilcox Sand Immediately above Confining Zone	Wellhead	Safety and compliance
	Downhole pressure/temperature gauge	Basal Wilcox Sand	Perforations	Verify that no fluid is escaping from the Sequestration Complex
VSP stations or other method	Time-lapse VSP or other time-lapse method	Reservoir – Plume Tracking	Surface and in Wellbore	Monitor CO_2 plume size and reservoir integrity
Atmospheric monitoring tower and testing sites	Eddy covariance tower	Surface Air	Dedicated Server	Identify CO_2 concentrations above ambient background levels
	Landfill gas meter			
Ecosystem Stress monitoring	Satellite imagery from Landsat 9 and Sentinel-2 imaging platforms	Vegetative Conditions	Dedicated Server	Measure potential stress resulting from elevated CO_2 in soil

Monitoring Location	Instrument Type	Monitoring Target (Formation or Other)	Data Collection Location(s)	Explanation
Soil gas sampling sites	Soil gas probe	Shallow Soil Gas	Dedicated server	Identify potential CO_2 leaks and discern the source(s) of detected CO_2 to either natural or anthropogenic sources
Soil sampling sites	Direct push drill rig/ hand auger	Shallow Soil	Dedicated server	Establish baseline site soil characteristics.

[1] If deployed

Table 3. Geophysical Survey Summary.

Monitoring Location	Instrument Type	Monitoring Target (Formation or Other)	Data Collection Location(s)	Explanation
In-zone monitoring wells	Time-lapse VSP or other time-lapse method	Tuscaloosa	Surface and in Wellbore	Monitor plume extent and potential out of zone movement
		Annona		
		Wilcox		

A.3.c. Geographic Locations

The injection wells will be located at the Port of Columbia Facility and shown in Figure 2 of the Testing and Monitoring Plan. Direct monitoring in two wells completed into the Tuscaloosa Injection Zone will be used to detect and define the dimensions of the carbon dioxide plume during well operations. The Bradford-Brown Trust Shipp No. 1 (SN20131) well, located approximately 10,152 feet up dip of the injection wells, will be re-entered and repurposed by recompletion of the well across the entire Tuscaloosa Sandstone (well currently penetrated the upper one-third of the Tuscaloosa interval). This well is optimally located in the direct plume path (up dip) of the sequestered carbon dioxide. Real-time, continuous pressure-monitoring will be performed in the well and the well will be completed to allow for fluid sampling, if needed. A second monitoring well will leverage the installed Whitetail Operating, LLC, Louisiana Green Fuels #1 stratigraphic test well, located approximately 5,273 feet southeast of the proposed injection wells. The well will also be fitted with downhole pressure gauges (gauges will be referenced to ground level at each well) and will be configured to allow for fluid sampling, if needed, based on carbon dioxide encountering the wellbore. Each well will also have a transmitter gauge at surface to continuously record tubing pressure. Experience shows, such as at the Frio Project, that carbon dioxide will rapidly evacuate the wellbore fluids in a monitoring well that is open to the Injection Zone, which will result in increased wellhead pressures due to the lighter column of gas replacing the brine fluid column.

Above zone monitoring interval (AZMI) will occur in wells installed in areas where In-zone monitoring is already occurring. The initial AZMI Monitoring zone for the sequestration project is the Annona Sandstone. The Annona Sandstone is a blanket sand that extends throughout the Area of Review. Injection Zone (IZ) Monitoring and AZMI Monitoring wells are expected to be engineered as multi-zone completions, if feasible.

Above Confining Zone Monitoring Interval (ACZMI) will occur in a well drilled and completed in the basal Wilcox on the Port of Columbia Facility property. There is a porous Wilcox sandstone located at a depth of 2,846 to 2,866 feet below ground level (referenced to the Southwestern Energy Production Company CPC #1 well (SN235656), located near the southeastern corner of the facility

property) that is stratigraphically just above the top of the Midway Shale. The ACZMI Monitoring well is located near the point of carbon dioxide injection, where elevated formation pressure in the Tuscaloosa are greatest.

Atmospheric monitoring will occur continuously at an Eddy Covairance tower adjacent to proposed injection well #1, and intermittently via a portable gas meter adjacent to proposed injection wells, monitoring wells, and soil gas monitoring sites.

Ecosystem stress monitoring will be assessed via satellite imagery and limited ground-based vegetation surverys which will capture the entirety of the AoR and surrounding reference areas, and "quadrants" of similar vegetaion and terrain, respectively.

Permanent subsurface soil gas probes will be installed at 12 to 15 representative locations including, at a minimum, three probe sites in the vicinity of the initial injection well site, and one probe site at each of the remaining four proposed injection well sites, the two Tuscaloosa/Annona Sand monitoring wells, and the single Lower Wilcox monitoring well. One or more probes may also be installed within the ecosystem stress monitoring reference areas. The remaining locations of the soil gas probe sites will be determined as more data and information become available for the site during the baseline and operational phases of the project. Soil characterization samples will be collected concurrently at these soil gas probe locations during their installation.

Figure 1 of the Testing and Monitoring Plan presents a cross sectional view of the deep subsurface monitoring network. Figures 3 and 4 of the Testing and Monitoring Plan present the ecosystem stress monitoring areas that will be assessed.

A.3.d. Resource and Time Constraints

No additional resource or time constraints have been identified for the Testing and Monitoring plan beyond project funding levels and the proposed timeline.

A.4. Quality Objectives and Criteria

A.4.a. Performance/Measurement Criteria

The objective of the QASP is to develop and implement procedures for surface, near-surface, and

subsurface testing and monitoring, field sampling, laboratory analyses, and reporting which will provide results allowing to track and meet the requirements of the non-endangerment goals of the project. Groundwater monitoring will be conducted during the pre-injection, injection, and post-injection phases of the project. Public water supply wells operated by the East Columbia Water District will be selected as locations for water quality sampling. Additionally, water quality monitoring in the basal Wilcox, immediately above the Midway Confining Zone, will be conducted during the pre-injection, injection, and post-injection phases of the project. The analytical and field parameters for fluid samples are listed in Table 4. Tables 5 and 6 provide the analytical parameters for carbon dioxide stream monitoring and corrosion coupon assessment, respectively, while Table 7 details the measurement parameters for the field gauges. Atmospheric, ecosystem stress, and soil gas monitoring will be conducted during the pre-injection and injection phases of the project. Additionally, soil samples will be collected during soil gas probe installation in the pre-injection phase. Analytical and field parameters for continuous and intermittent surface air testing are presented on Tables 8 and 9, respectively. Tables 10 and 11 provide the analytical and field parameters for soil gas and soil samples, respectively. The testing and monitoring outputs are presented in Table 12.

Quality objectives for satellite imagery data and associated indices utilized for ecosystem stress monitoring are met by: i) standard imagery source reliability by accredited agencies such as the United States Geological Survey (USGS) and the European Space Agency (ESA); and ii) imagery processing product reliability tailored to these sources (Dwyer et al., 2018; Vermote et al., 2016; ESA Product Types (web); IDB Project, 2022).

Note that these tables will be periodically updated as the vendor selection and onboarding process advance. Adjustments will also be needed as the relevant scope of work is adopted and implemented.

Table 4. Summary of Analytical and Field Parameters for Fluid Samples in Wilcox All analysis will be performed by an Accredited Louisiana Laboratory.

Parameters	Analytical Methods(1)	Detection Limit/Range	Typical Precisions	QC Requirements
Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb, Se, and Tl	ICP-MS, EPA Method 6020	0.001 to 0.1 mg/L (analyte, dilution, and matrix dependent)	±15%	Daily calibration; duplicates and matrix spikes at 10% or greater frequency
Ca, Fe, K, Mg, Na, and Si	ICP-OES, EPA Method 6010B	0.005 to 0.5 mg/L (analyte, dilution, and matrix dependent)	±15%	Daily calibration; duplicates and matrix spikes at 10% or greater frequency
Anions: Br, Cl, F, NO_3, and SO_4	Ion chromatography, EPA Method 300.0	0.02 to 0.13 mg/L (analyte, dilution, and matrix dependent)	±15%	Daily calibration; duplicates and matrix spikes at 10% or greater frequency
Dissolved CO_2	Coulometric titration, ASTM D513-11	25 mg/L	±15%	Duplicate measurements; standards at 10% or greater frequency
Alkalinity	APHA 2320B	4 mg/L	±3 mg/L	Duplicate analysis
Total dissolved solids	Gravimetry, APHA 2540C	12 mg/L	±10%	Balance calibration, duplicate analysis
Isotopes: $\delta^{13}C$ of DIC	Isotope ratio mass spectrometry(2)	12.2 mg/L HCO_3^- for $\delta^{13}C$	±0.15‰ for $\delta^{13}C$	10% duplicates; 4 standards per batch
Water density (field)	Oscillating body method	0.0000 to 2.0000	±0.0002 g/mL	Duplicate measurements

pH (field)	EPA Method 150.1	2 to 12 pH units	±0.2 pH unit	User calibration per manufacturer recommendation
Specific conductance (field)	APHA 2510	0 to 200 mS/cm	±1% of reading	User calibration per manufacturer recommendation
Temperature (field)	Thermocouple	-5 to 50 ºC	±0.2 ºC	Factory calibration

Note 1: An equivalent method may be employed with the prior approval of the UIC Program Director.
Note 2: Gas evolution technique by Atekwana and Krishnamurthy (1998), with modifications made by Hackley et al (2007).
Note 3: ICP = inductively coupled plasma; MS = mass spectrometry; OES = optical emission spectrometry

Table 5. Summary of Analytical Parameters for CO_2 Stream at the surface. All analysis will be performed by an Accredited Louisiana Laboratory.

Parameters	Analytical Methods(1)	Detection Limit/Range	Typical Precisions	QC Requirements
Carbon Dioxide	ISBT 2.0 Caustic Absorption Zahm-Nagel	99.00 to 99.99%	±10% of reading	User calibration per manufacturer recommendation
	ALI Method SAM 4.1 Subtraction Method (GC/DID)	1 ppm for each target analyte (analyte dependent)	5-10% relative across the range	Duplicate analysis within 10% of each other
	GC/TCD	0.1 to 100%	5-10% relative across the range, RT±0.1 min	Standard with every sample, duplicate analysis within 10% of each other
Oxygen	ISBT 4.0 (GC/DID) GC/TCD	1 to 5,000 µL/L (ppm by volume)	±10% of reading	Daily standard within 10% of calibration, secondary standard after calibration
		0.1 to 100%	5-10% relative across the range, RT±0.1 min	Daily standard, duplicate analysis within 10% of each other
Nitrogen	ISBT 4.0 (GC/DID)	5 to 100 µL/L (ppm by volume)	±20% of reading	Daily standard within 10% of calibration, secondary standard after calibration
	GC/TCD	0.1 to 100%	5-10% relative across the range, RT±0.1 min	Daily standard, duplicate analysis within 10% of each other

Carbon Monoxide	ISBT 5.0 Colorimetric ISBT 4.0 (GC/DID)	1 to 5,000 µL/L (ppm by volume) 1 to 5,000 µL/L (ppm by volume)	±10% of reading ±10% of reading	Duplicate analysis Daily standard within 10% of calibration, secondary standard after calibration
Hydrogen Sulfide	ISBT 14.0 (GC/SCD)	0.01 to 50 µL/L (ppm by volume) – dilution dependent	5-10% of reading relative across the range	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Nitrogen Oxides	ISBT 7.0 Colorimetric	0.2 to 5 µL/L (ppm by volume)	±20% of reading	Duplicate analysis
Sulfur Dioxide	ISBT 14.0 (GC/SCD)	0.01 to 50 µL/L (ppm by volume) – dilution dependent	5-10% of reading relative across the range	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Methane	ISBT 10.1 (GC/FID)	0.1 to 1,000 µL/L (ppm by volume) – dilution dependent	5-10% of reading relative across the range	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Total Hydrocarbons	ISBT 10.0 THA (FID)	1 to 10,000 µL/L (ppm by volume) – dilution dependent	5-10% of reading relative across the range	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Acetaldehyde	ISBT 11.0 (GC/FID)	0.1 to 100 µL/L (ppm by volume) – dilution dependent	5-10% of reading relative across the range	Daily blank, daily standard within 10% of calibration, secondary standard after calibration

Ethanol	ISBT 11.0 (GC/FID)	0.1 to 100 µL/L (ppm by volume) – dilution dependent	5-10% of reading relative across the range	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Water, Hydrogen, Carbonyl Sulfide, Argon, Glycol				

Note 1: An equivalent method may be employed with the prior approval of the UIC Program Director.

Table 6. Summary of Analytical Parameters for Corrosion Coupons.

Parameters	Analytical Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Mass	NACE Standard RP0775-2005 Item No. 21017	0.005 mg	±2%	Annual calibration of scale (3rd party)
Thickness	NACE Standard RP0775-2005 Item No. 21017	0.001 mm	±0.005 mm	Factory calibration

Table 7. Summary of Measurement Parameters for Field Gauges.

Parameters	Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Booster pump discharge pressure (PIT-012)	ANSI Z540-1-1994	±0.001 psi / 0-3,000 psi	±0.01 psi	Annual calibration of scale or to manufacturers specs (3rd party)
Injection tubing temperature (TIT-019)	ANSI Z540-1-1994	±0.001 F / 0-500 F	±0.01 F	Annual calibration of scale or to manufacturers specs (3rd party)
Annulus pressure (PIT-014)	ANSI Z540-1-1994	±0.001 psi / 0-3,000 psi	±0.01 psi	Annual calibration of scale or to manufacturers specs (3rd party)
Injection tubing pressure (PIT-009)	ANSI Z540-1-1994	±0.001 psi / 0-3,000 psi	±0.01 psi	Annual calibration of scale or to manufacturers specs (3rd party)
Injection mass flow rate (FIT-006)	Direct measurement	±0.1% of rate/50,522-303,133 lbs/hr	±0.01 lbs/hr	Annual calibration of scale or to manufacturers specs (3rd party)
Downhole pressure	Direct measurement	±0.1 psi / 0-10,000 psi	±0.2% of scale	Annual calibration of scale or verification against wireline gauge
Downhole temperature	Direct measurement	±0.01 ^{o}C/125 ^{o}C	±0.5% of scale	Annual calibration of scale or verification against wireline gauge

Table 8. Summary of Analytical Parameters for Continuous Surface Testing.

Parameters	Analytical Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Carbon Dioxide	Non-dispersive infrared spectroscopy	0.11 ppm/ 0 to 3000 ppm	±1%	Windows® based software supports all setup, configuration, and calibration functions through Ethernet connection
Methane	Single-mode tunable near-infrared laser	5 ppb/ 0 to 25 ppm at -25 °C or 0 to 40 ppm at 50 °C	< 1% to 2%	Windows® based software supports all setup, configuration, and calibration functions through Ethernet connection
Hydrogen Dioxide	Non-dispersive infrared spectroscopy	4.7 ppb/ 0 to 60 ppm	±1%	Windows® based software supports all setup, configuration, and calibration functions through Ethernet connection
Nitrous Oxide	Laser-based absorption spectroscopy	1 ppb/ 0 to 100 ppm	0.2 to 0.4 ppb	Built in web server based software supports all setup, configuration, and calibration functions through Ethernet connection
Wind Direction	Ultrasonic sound pulse between upper and	0 to 359°	< ±1° RMS	Pre-custom calibration

Parameters	Analytical Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Wind Speed	opposite lower transducers	0 to 45 m/s	< 1% RMS	
Soil Moisture	Electromagnetic signal	Dry to fully saturated	±0.01 to ±0.03	Pre-custom calibration
Soil Temperature		-10 to 55 °C	±0.1 °C	
Soil Heat Flux	Differential temperature across the ceramics-plastic composite body of thermopile	+2000 to -2000 Wm^{-2}	within +5 to -15%	
Net Radiation	Net pyrradiometer: thermopile detector fitted with PTFE coated conical absorbers	200 nm to 100 µm	Not specified	Pre-custom calibration and follow-up manufacturer calibration every 2 years

Parameters	Analytical Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Relative Humidity	Polymer sensor deposited between two conductive electrodes	0 to 100%RH	±1%RH (0 – 90 %RH) and ±1.7 %RH (90 – 100 %RH) from 15 to 25 °C ±(1.0 + 0.008 x reading) %RH from -20 to 40 °C ±(1.2 + 0.012 x reading) %RH from -40 to -20 °C and from 40 to 60 °C ±(1.4 + 0.032 x reading) %RH from -60 to -40 °C	Manual calibration using a pc with a USB cable, the push buttons, or the MI70 indicator
Barometric Pressure	Pressure tranducer	50 to 110 kPa	0.4 kPa	Pre-custom calibration
Ambient Temperature	Polymer sensor deposited between two conductive electrodes	-80 to 60 °C	±(0.226 - 0.0028 x temperature) °C from -80 to 20 °C ±(0.055 + 0.0057 x temperature) °C from 20 to 60 °C	Pre-custom calibration
Precipitation	Remote tipping bucket	Up to 2” per hour	±1%	Routine cleaning of debris from filter screen and occasional manual calibration verification

Table 9. Summary of Analytical Parameters for Intermittent Surface Air Testing.

Parameters	Analytical Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Carbon Dioxide	Dual wavelength infrared cell	0 to 100%	0-5%: ±0.3% 5-15%: ±1.0% 15% - Full Scale: ±3.0%	User calibration per manufacturer recommendation
Methane	Dual wavelength infrared cell	0 to 100%	0-5%: ±0.3% 5-15%: ±1.0% 15% - Full Scale: ±3.0%	User calibration per manufacturer recommendation
Oxygen	Internal electrochemical cell	0 to 25%	0-5%: ±1.0% 5-15%: ±1.0% 15% - Full Scale: ±1.0%	User calibration per manufacturer recommendation

Table 10. Summary of Measurement Parameters for Soil Gas Samples.

Parameters	Methods	Detection Limit/Range	Typical Precisions	QC Requirements
CO_2, N_2, O_2	Gas chromatography	CO_2: 50 ppm N_2 and O_2: 100 ppm	for CO2 (> 1.5%) ±0.6% (of measured value) for CO2 (< 0.05%) ±1.7% (of measured value) for N2 and O2 (>10%) ±0.5% (of measured value)	At a rate of 20% of the samples analyzed: A lab check standard or sample duplicate is analyzed every 5th run with a lab standard being run first every day. Method based on ASTM D1945.
CH_4, C1-C5	Gas chromatography	CH_4: 2 ppm C2 - C6+: 1ppm	CH4: ±0.4 to 1% (of measured value) C2 - C4: ±0.4 to 1% (of measured value) C5 - C6+: ±2 to 4% (of measured value)	At a rate of 20% of the samples analyzed: A lab check standard or sample duplicate is analyzed every 5th run with a lab standard being run first every day. Method based on ASTM D1945.
Helium	Gas chromatography	50 ppm	±2%	At a rate of 20% of the samples analyzed: A lab check standard or sample duplicate is analyzed every 5th run with a lab standard being run first every day. Method based on ASTM D1945.

$\delta^{13}C$ of CO_2 and CH_4	High precision, dual inlet IRMS	CO_2 and CH_4: 0.25%	CO_2 and CH_4: ±0.1%	At a rate of 20% of the samples analyzed: A lab check standard or sample duplicate is analyzed every 5th run with a lab standard being run first every day. Method similar to Edman, J.D., 2007, Newsletter of the Rocky Mountain Association of Geologists, v. 56, no. 8.
δD of CH_4	High precision, dual inlet IRMS	CH_4: 0.5%	CH_4: ±3.5%	At a rate of 20% of the samples analyzed: A lab check standard or sample duplicate is analyzed every 5th run with a lab standard being run first every day. Method similar to Edman, J.D., 2007, Newsletter of the Rocky Mountain Association of Geologists, v. 56, no. 8.
^{14}C of CO_2 and CH_4	Accelerated mass spectrometry	0.44 pMC/ 0.44 pMC – 198 pMC	0.02 pMC - 0.5 pMC	NIST suite, IAEA standards, AMS wheel, and QA report

Table 11. Summary of Analytical Parameters for Soil Samples.

Parameters	Analytical Methods	Detection Limit/Range	Typical Precisions	QC Requirements
Total Organic Carbon (TOC)	Walkley Black 9060A	0.02 wt%	±20%	Lab Control/ Lab Control Duplicate, Matrix Spike/ Matrix Spike Duplicate samples, instrument calibration, field duplicates
Salinity	SM 2520B	5 umhos/cm	±20%	Lab Control/ Lab Control Duplicate samples, instrument calibration, field duplicates
Percent Moisture	SM 2540G	0.1 - 100%	±20%	Instrument calibration, field duplicates

Table 12. Actionable Testing and Monitoring Outputs.

Activity or Parameter	Project Action Limit	Detection Limit	Anticipated Reading
External mechanical integrity (DAS/DTS fiber-optic cable) [4]	Measure thermal and acoustic anomalies between normal and shut-in operations to detect potential leakage into USDW through vertical channels adjacent to injection wellbore(s)	(1)	(1)
Internal mechanical integrity (pulsed neutron logging)	Measure response to neutron pulse, through casing, to detect potential leakage in casing, tubing, or packer	Tool Logging Mode and logging speed dependent	No statistically significant difference from baseline log run.
Surface pressure gauges	Pressure approaching modeled or permitted limit	(1)	(1)
Downhole pressure gauges	Pressure approaching modeled or permitted limit	(1)	(1)
Groundwater and environmental parameters (including surface air, ecosystem stress, and soil gas)	A statistically significant departure between observed and baseline/ seasonal parameter patterns	(2)	Within statistical test of baseline/seasonal values (Fed Reg v. 53, No. 196, 39720-39731)
Water quality measurements in ACZMI Wilcox Sand	A statistically significant departure between observed and baseline/ seasonal parameter patterns	(1)	Within statistical test of baseline/seasonal values (Fed Reg v. 53, No. 196, 39720-39731)

Activity or Parameter	Project Action Limit	Detection Limit	Anticipated Reading
Mismatch between modeled and observed in-zone pressure response	Action when pressure response is outside of bounds model outcomes by 1.5X or approaching maximum permit values	(1)	Formation pressures within bounds of model outcomes
Mismatch between modeled and observed plume migration	Action when plume is outside of bounds of the Sequestration Complex	Dependent of rock properties and contrast in density due to fluid saturations	Plume geometry within bounds of model outcomes

Note 1: These data are to be negotiated during well engineering design, after assessment of available instruments.
Note 2: The methodology for anomaly detection and attribution requires data collection over several years to identify natural and spatial variation and comparison to fluid, surface air, and soil gascompositions and vegetatitve conditions to identify a leakage signal. This will be added to the monitoring plan and used to follow up incident or allegation to attribute signal.
Note 3: Actual mismatch between modeled and observed in-zone pressure response and plume tracking depends on recalibration of the model with new data, followed by a forward model to determine any unacceptable outcomes, result from the production of pressure and plume evolution.

Note 4: If deployed

A.4.b. Precision

Precision will be determined after the different vendors and contractors are selected, per their individual standard operating procedures. Tables 13 to 18 summarize the detailed specifications for the downhole and field gauges. In the wellbore, the downhole gauges include pressure and temperature measurements. At the surface, the field gauges include injection tubing pressure and temperature, annulus pressure, and CO_2 mass flow rate.

Table 13. Pressure and Temperature—Downhole Gauge Specifications.

Parameter	Value
Calibrated working pressure range	Atmospheric to 10,000 psi
Initial pressure accuracy	±0.2% over full scale
Pressure resolution	±0.1 psi
Pressure drift stability	±0.2% over full scale per annum

Calibrated working temperature range	0-125 ºC
Initial temperature accuracy	±0.5% over full scale
Temperature resolution	±0.01 ºC
Temperature drift stability	±0.2% over full scale per annum
Max temperature	±125 ºC
Instrument calibration frequency	Annual verification or per manufactures specification

Table 14. Pressure Field Gauge—Injection Tubing Pressure.

Parameter	Value
Calibrated working pressure range	0 to 3,000 psi
Initial pressure accuracy	<±0.25% over full scale
Pressure resolution	<±1 psi
Pressure drift stability	To be determined

Table 15. Pressure Field Gauge—Annulus Pressure.

Parameter	Value
Calibrated working pressure range	0 to 3,000 psi
Initial pressure accuracy	<±0.25% over full scale
Pressure resolution	<±1 psi
Pressure drift stability	To be determined

Table 16. Temperature Field Gauge—Injection Tubing Temperature.

Parameter	Value
Calibrated working temperature range	0 to 500 ºF
Initial temperature accuracy	<±0.4% over full scale
Temperature resolution	<±4 ºF
Temperature drift stability	To be determined

Table 17. Mass Flow Rate Field Gauge—CO_2 Mass Flow Rate.

Parameter	Value
Calibrated working flow rate range	± 100 bar
Initial mass flow rate accuracy	±0.1 % of rate - liquid
Mass flow rate repeatibility	±0.05 % of rate - liquid
Mass flow rate drift stability	To be determined after first year

Table 18. Representative Logging Tool Specifications.

Parameter	Pulsed Neutron	Cement Bond	Casing Imager
Logging speed	3.600 ft/hr	3,600 ft/hr	Variable 400 to 4,500 ft/hr
Vertical resolution	15 inches	3 feet	6 inches
Investigation	Fluid Saturation	Quality of bond	Evaluation of casing and cement
Temperature rating	350 ºF	350 ºF	350 ºF
Pressure rating	15,000 psi	20,000 psi	20,000 psi

A.4.c. Bias

Laboratory assessment of analytical bias will be the responsibility of the individual laboratories per their standard operating procedures and analytical methodologies. For gauge and logging measurements, no bias is reasonably expected.

A.4.d. Representativeness

For groundwater, surface air, soil gas, and soil sampling, data representativeness expresses the degree to which data accurately and precisely represents a characteristic subset of a given population, parameter variations at a sampling point, a process condition, or an environmental condition. The groundwater, surface air, soil gas, and soil sampling networks have been designed to provide data representativeness of site conditions. For analytical results of individual groundwater samples, representativeness will be estimated by ion and mass balances. Ion balances

with ±10% error or less will be considered valid. Mass balance assessment will be used in cases where the ion balance show an error greater than ±10% to help determine the source of error. For a sample and its duplicate, if the relative percent difference is greater than 10, the sample may be considered non-representative.

Similarly, vegetation surveys will be conducted utilizing a "quadrant"-like approach, where similar vegetation and terrain areas will be characterized by their primary vegetation types in the Area of Review and surrounding reference areas. For each analysis during pre-injection and injection, all available satellite images will be processed into quarterly composite images to be representative of each season.

A.4.e. Completeness

For groundwater, surface air, soil gas, and soil sampling and ecosystem stress monitoring, data completeness is a measure of the amount of valid data obtained from a measurement system compared to the amount that was expected to be obtained under normal conditions. It is anticipated that data completeness of 90% will be acceptable to meet the project's monitoring goals. For direct pressure and temperature measurements and continuous surface air monitoring, it is expected that data will be recorded no less than 90% of the time.

A.4.f. Comparability

Data comparability expresses the confidence with which one dataset can be compared to another. The datasets to be generated by this project will be very comparable to future datasets because of the systematic use of standard methods and the level of QA/QC effort. If historical groundwater quality, surface air, soil gas, and soil data become available from other sources, their applicability to the project and their level of quality will be assessed prior to use. Direct pressure, temperature, and logging measurements are directly comparable to previously obtained data. If necessary, historical satellite imagery may be obtained and directly compared to imagery obtained during the baseline and operational phases of the project.

A.4.g. Method Sensitivity

The sensitivity of the testing and monitoring methods employed for this project will be discussed

with the UIC Program Director after the draft of the Testing and Monitoring Plan has been approved.

A.5. Special Training/Certifications

A.5.a. Specialized Training and Certifications

The geophysical survey equipment and wireline logging tools will be operated by trained, qualified, and certified personnel, with documentation provided by the selected vendors. The subsequent data will be processed and analyzed according to industry standards. No specialized certifications are required for personnel conducting groundwater, surface air, soil gas, or soil sampling, but field sampling will be conducted by trained personnel according to the project specific sampling procedures which will be provided by Louisiana Green Fuels.

A.5.b/c. Training Provider and Responsibility

Training for personnel will be provided by the operator or subcontractor responsible for the data collection activity.

A.6. Documentation and Records

A.6.a. Report Format and Package Information

A semi-annual report from Louisiana Green Fuels to the USEPA and CARB will contain all required project data, including testing and monitoring information as specified by the UIC Class VI permit and LCFS Protocol. Data will be provided in electronic or other formats as requested by the UIC or CARB Program Director.

A.6.b. Other Project Documents, Records, and Electronic Files

Other documents, records, and electronic files such as well logs, test results, or other data will be provided as requested by the UIC Program Director.

A.6.c/d. Data Storage and Duration

Louisiana Green Fuels or a designated contractor will maintain the required project data as provided elsewhere in the permit.

A.6.e. QASP Distribution Responsibility

Louisiana Green Fuels will be responsible for ensuring that all those on the distribution list will receive the most current copy of the approved Quality Assurance and Surveillance Plan.

B. DATA GENERATION AND ACQUISITION

B.1. Sampling Process Design

Discussion in this section focuses on fluid, soil, and soil gas sampling and does not address monitoring methods that do not gather physical samples (e.g., logging, seismic monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring).

During the pre-injection and injection phases, groundwater sampling and testing are planned to include an extensive set of chemical parameters to establish aqueous geochemical reference data. Parameters will include selected constituents that: (1) have primary and secondary USEPA drinking water maximum contaminant levels, (2) are the most responsive to interaction with CO_2 or brine, (3) are needed for water quality control, and (4) may be needed for geochemical modeling. The full set of parameters for each sampling interval is given in Table 4. After a sufficient baseline is established, monitoring scope during the post-injection phase may shift to a subset of indicator parameters that are (1) the most responsive to interaction with CO_2 or brine and (2) are needed for water quality control. Implementation of a reduced set of parameters will be done in consultation with the USEPA and CARB. Similarly, during the pre-injection and injection phases, soil gas sampling and testing are planned to include an extensive set of chemical parameters (see Table 10) to establish near-surface geochemical reference data. Parameters will include selected constituents that are the most responsive to interaction with CO_2. During soil gas probe site installation, soil samples will be collected in general accordance with EPA Method LSASDPROC-300-R4 (USEPA, 2020a) for the laboratory analysis of soil moisture, organic carbon content, and salinity according to USDA methods to establish site characteristics pre-injection.

Isotopic analyses can be performed on baseline groundwater and soil gas samples to the degree that the information helps verify a condition or establish an understanding of non-project related variations. In fact, baseline isotopic analyses of soil gas will be conducted to help determine natural background variability. For non-baseline samples, isotopic analyses may be reduced in all monitoring wells and soil gas probe sites if a review of the historical project results or other data determines that further sampling for isotopes is not needed. During any period where a reduced set of analytes is used, if statistically significant trends are observed that are the result of

unintended CO_2 or brine migration, the analytical list will be expanded to the full set of monitoring parameters.

The groundwater, soil, and soil gas samples will be analyzed by third-party laboratories meeting the requirements under the Louisiana Environmental Laboratory Accreditation Program. All other samples will be analyzed by the operator or a third-party laboratory. Dissolved CO_2 will be analyzed using methods consistent with Test Method B of ASTM D513-06, "Standard Test Methods for Total and Dissolved Carbon Dioxide in Water" or equivalent. Isotopic analysis will be conducted using established methods.

B.1.a. Design Strategy

CO_2 Stream Monitoring Strategy

The primary purpose of analyzing the carbon dioxide stream is to evaluate the potential interactions of carbon dioxide and/or other constituents of the injectate with formation solids and fluids. This analysis can also identify (or rule out) potential interactions with well materials. Establishing the chemical composition of the injectate also supports the determination of whether the injectate meets the qualifications of hazardous waste under the Resource Conservation and Recovery Act (RCRA), 42 U.S.C. §6901 et seq. (1976), and/or the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), 42 U.S.C. §9601 et seq. (1980). Additionally, monitoring the chemical and physical characteristics of the carbon dioxide (e.g., isotopic signature, other constituents) may help distinguish the injectate from the native fluids and gases if unintended leakage from the storage reservoir occurred.

Injectate monitoring is required at a sufficient frequency to detect changes to any chemical and physical properties that may result in a deviation from the permitted specifications. Analyses of the injected stream will occur quarterly or when a "know" change in the process that could affect stream composition occurs.

Calibration of transmitters used to monitor pressures, temperatures, and flow rates of CO_2 into the injection well(s) at the injection well(s) and at the monitoring well(s) will be conducted annually.

Reports will specify test equipment used to calibrate the transmitters, including test equipment manufacturers, model numbers, serial numbers, calibration dates, and expiration dates.

Corrosion Monitoring Strategy

Corrosion coupon analyses will be conducted quarterly to aid in ensuring the mechanical integrity of the equipment in contact with the carbon dioxide. Coupons will be sent quarterly to a third-party laboratory for analysis conducted in accordance with NACE Standard RP0775-2005 Item No. 21017 (or similar such as ASTM G1 – 03 (2017)) to determine and document corrosion wear rates based on mass loss.

Shallow Groundwater Monitoring Strategy

Dedicated monitoring of East Columbia Water District public water supply wells will be chosen for shallow groundwater monitoring. These wells will be carefully selected to provide a spatial distribution around the planned CO_2 injection well location(s).

Deep Groundwater Monitoring Strategy

Quarterly luid sampling in the basal Wilcox sand that immediately overlies the Midway Shale Confining Zone will be used in combination with pressure monitoring and temperature monitoring to determine if leakage is occurring at or near the injection well(s). The basal Wilcox sandstone interval has sufficient permeability (+/-100 mD) such that pressure monitoring at the monitoring wells would detect a failure of the confining zone should it occur. MIT testing and DTS/DAS monitoring at the injection well(s), if installed, will also provide data to insure the mechanical integrity of the well(s) is maintained.

With the planned sampling initiated one year ahead of injection and quarterly monitoring frequencies, it is expected that baseline conditions can be documented, natural variability in the baseline conditions can be characterized, unintended brine or CO_2 leakage could be detected if it occurred, and sufficient data can be collected to demonstrate that the effects of CO_2 injection are limited to the intended storage reservoir.

Soil Gas Monitoring Strategy

Soil gas sampling will be conducted during i) baseline on a monthly basis (with isotopic analyses conducted quarterly) to establish natural background variability within the Area of Review, and ii) injection on a quarterly basis to monitor any changes in the environmental conditions that could be a consequence of a leakage from the storage reservoir. Permanent subsurface soil gas probes will be installed at 12 to 15 representative locations throughout the surface projection of the Area of Review. The baseline soil gas monitoring network will depend on appropriate land access agreements, and will include, at a minimum, three probe sites in the vicinity of the initial injection well site, and one probe site at each of the remaining four proposed injection well sites, the two Tuscaloosa/Annona Sand monitoring wells, and the single Lower Wilcox monitoring well. One or more probes may also be installed within the ecosystem stress monitoring reference areas. The remaining locations of the soil gas probe sites will be determined as more data and information become available for the site during the baseline and operational phases of the project. It is anticipated that the baseline soil gas monitoring network will be utilized during the operational phase as well, as needed.

Soil Characterization Strategy

Soil sampling will occur concurrently with soil gas probe installation sites. The purpose of collecting these samples is to characterize pre-injection soil conditions that may be referenced as a baseline dataset, as needed, for support in leakage detection strategies.

B.1.b. Type and Number of Samples/Test Runs

To be updated when UIC Program Director has approved draft permit.

B.1.c. Site/Sampling Locations

To be updated when UIC Program Director has approved draft permit.

B.1.d. Sampling Site Contingency

To be updated when UIC Program Director has approved draft permit.

B.1.e. Activity Schedule

To be updated when UIC Program Director has approved draft permit.

B.1.f. Critical/Informational Data

During both groundwater, soil gas, and soil sampling and analytical efforts, detailed field and laboratory documentation will be taken. Documentation will be recorded in field and laboratory forms and notebooks. Critical information will include date and time of activity, person/s performing activity, location of activity (well vs. field sampling) or instrument (lab analysis), field or laboratory instrument calibration data, and field parameter values. For laboratory analyses, much of the critical data are generated during the analysis and provided to end users in digital and printed formats. Noncritical data may include appearance and odor of the sample, problems with well or sampling equipment, and weather conditions.

B.1.g. Sources of Variability

Potential sources of variability related to monitoring activities include (1) natural variation in fluid quality, soil gas composition, soil, formation pressure and temperature, and seismic activity; (2) variation in fluid quality, soil gas composition, soil, formation pressure and temperature, and seismic activity due to project operations; (3) changes in recharge due to rainfall, drought, and snowfall; (4) changes in instrument calibration during sampling or analytical activity; 5) different staff collecting or analyzing samples; (6) differences in environmental conditions during field sampling activities; (7) changes in analytical data quality during life of project; and (8) data entry errors related to maintaining project database.

Activities to eliminate, reduce, or reconcile variability related to monitoring activities include (1) collecting long-term baseline data to observe and document natural variation in monitoring parameters, (2) evaluating data in timely manner after collection to observe anomalies in data that can be addressed, resampled or reanalyzed, (3) conducting statistical analysis of monitoring data to determine whether variability in a dataset is the result of project activities or natural variation, (4) maintaining weather-related data using on-site weather monitoring data or data collected near project site (such as from local airports), (5) checking instrument calibration before, during and after sampling or sample analysis, (6) thoroughly training staff, (7) conducting laboratory quality assurance checks using third-party reference materials, and/or blind and/or replicate sample checks, and (8) developing a systematic review process of data that can include sample-specific

data quality checks (i.e., cation/anion balance for aqueous samples).

B.2. Sampling Methods

Discussion in this section applys to physical samples and does not apply to logging, seismic monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring.

B.2.a/b. Sampling SOPs

Groundwater samples will be collected primarily using a low-flow sampling method or similar, that is consistent with ASTM D6452-99, Yeskis and Zavala (2002), or Puls and Barcelona (1996). If a flow-through cell is not used, field parameters will be measured in grab samples. Groundwater wells will be purged to ensure samples are representative of formation water quality. Static water levels in each well will be determined using an electronic water level indicator before any purging or sampling activities begin. Dedicated pumps (e.g., bladder pumps) may be installed in each monitoring well to minimize potential cross-contamination between wells. Groundwater pH, temperature, specific conductance, and dissolved oxygen will be monitored in the field using portable probes and a flow-through cell consistent with standard methods (e.g., APHA) given sufficient flow rates and volumes. Field chemistry probes will be calibrated at the beginning of each sampling day according to equipment manufacturer procedures using standard reference solutions. When a flow-through cell is used, field parameters will be continuously monitored and will be considered stable when three successive measurements made three minutes apart meet the criteria listed in Table 19.

After field parameters have stabilized, samples will be collected. Samples requiring filtration will be filtered through 0.45 μm flow-through filter cartridges as appropriate and consistent with ASTM D6564-00. Prior to sample collection, filters will be purged with a minimum of 100 mL of well water (or more if required by the filter manufacturer). For alkalinity and total CO_2 samples, a special effort will be made to minimize exposure to the atmosphere during filtration, collection in sample containers, and analysis. Samples will be properly preserved per analyte requirements.

Table 19. Stabilization Criteria of Water Quality Parameters During Shallow Well Purging.

Field Parameter	Stabilization Criteria
pH	±0.2 units
Temperature	±1 ºC
Specific conductance	±3% of reading in µS/cm
Dissolved oxygen	±10% of reading or 0.3 mg/L whichever is greater
Turbidity	Clarity

Soil gas sampling will be conducted in general accordance with operating procedures set forth in EPA Method LSASDPROC-307-R4 (USEPA, 2020a). During sample collection, a vacuum will be applied to the tubing on the surface to first purge the full length of the tubing, and second collect a soil gas sample in a 0.3-L IsoBag Gas Bag® using 60 mL gas-tight syringes, equipped with a 3-way valves. During soil gas sampling, a leakage test will be conducted by releasing helium gas as a tracer gas within a shroud over each soil gas sampling site.

Soil samples will be collected in general accordance with EPA Method LSASDPROC-300-R4 (USEPA, 2020b) during soil gas probe installation. Sample intervals will target various depths along the length of the boring to establish site soil characteristics pre-injection.

B.2.c. In-situ Monitoring

In-situ monitoring of groundwater and soil gas chemistry parameters is not currently planned.

B.2.d. Continuous Monitoring

Continuous monitoring of groundwater and soil gas chemistry parameters is not currently planned.

B.2.e. Sample Homogenization, Composition, Filtration

Sampling procedures is described in Section B.2.a/b.

B.2.f. Sample Containers and Volumes

Soil gas samples will be collected in 0.3-L IsoBag Gas Bag® supplied by the selected gecochemical laboratory. Soil samples will be collected in 4 oz. clear glass jars.

A summary of sample containers is presented in Tables 20 through 22.

B.2.g. Sample Preservation

For groundwater and other aqueous samples, the preservation methods provided in Tables 19 and 20 will be used. No preservation is required for soil gas samples.

B.2.h. Cleaning/Decontamination of Sampling Equipment

No cleaning or decontamination will be required for soil gas samples, as a brand new 60-mL gas-tight syringe will be utilized to collect each sample, and each soil gas probe site will include dedicated sampling tubing.

B.2.i. Support Facilities

Required support facilities will be determined in consultation with the selected sampling vendor.

B.2.j. Corrective Action, Personnel, and Documentation

Field staff will be responsible for properly testing equipment and performing corrective actions on broken or malfunctioning field equipment. If corrective action cannot be taken in the field, then equipment will be returned to the manufacturer for repair or replaced. Significant corrective actions affecting analytical results will be documented in field notes.

B.3. Sample Handling and Custody

Discussion in this section applys to physical samples, section does not apply to logging, seismic monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring.

Sample holding times given in Tables 19 thruough 21 are consistent with those described by USEPA (1974; 2020), American Public Health Association (APHA, 2005), Wood (1976), and ASTM Method D6517-00. After groundwater sampling, the samples will be placed in ice chests in the field and maintained thereafter at a preservation temperature of approximately 4°C until analysis. The samples will be transported to the designated laboratory within 24 hours. Analysis of the samples will be completed within the holding times listed in Tables 19 and 20. As appropriate and if required, alternative options to the sample containers and preservation techniques, approved by the UIC Program Director, will be implemented to meet analytical requirements.

B.3.a. Maximum Hold Time/Time Before Retrieval

See Tables 20 to 23.

B.3.b. Sample Transportation

Sampling transportation is described in the introduction of Section B.3.

B.3.c. Sampling Documentation

An analysis authorization form will be provided with each CO_2 gas stream sample for testing in the laboratory using the laboratory's standard form. Field notes will be collected for all groundwater, soil gas, and soil samples, then retained and archived for reference. The sample documentation is the responsibility of the groundwater, soil gas, and soil sampling personnel (third party vendor).

B.3.d. Sample Identification

All sample containers will have waterproof labels with information (as relevant) denoting project, sampling date, sampling location, sample identification number, sample type (e.g., freshwater or brine), analyte, volume, filtration used (if any), and preservative used (if any) using the analytical laboratory's standard sample identification form.

Table 20. Summary of Sample Containers, Preservation Treatments, and Holding Times for CO2 Gas Stream Analysis.

Sample	Volume/Container Material	Preservation Technique	Sample Holding time (max)
CO_2 gas stream	75 cc Mini Cylinder	None	5 Days

Table 21. Summary of Anticipated Sample Containers, Preservation Treatments, and Holding Times for Ground Water Samples.

Target Parameters	Volume/Container Material	Preservation Technique	Sample Holding Time
Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb, Se, and Tl	250 ml/HDPE	Filtered, nitric acid, cooled to 4°C	28 days

Ca, Fe, K, Mg, Na, and Si			
Anions: Br, Cl, F, NO3, and SO4	250 ml/HDPE	Filtered, nitric acid, cooled to 4°C	28 days
Dissolved CO_2	60 ml/HDPE	Filtered, cooled to 4°C	28 days
Alkalinity	500 ml/HDPE	Filtered, cooled to 4°C	28 days
Total dissolved solids	500 ml/HDPE	Cooled to 4°C	7 Days
Isotopes:	60 ml/HDPE	Filtered, cooled to 4°C	28 days
Field Confirmation: Water density pH Specific conductance Temperature	200 ml Glass	None	<1 hour

Table 22. Summary of Sample Containers, Preservation Treatments, and Holding Times for Soil Gas Samples.

Target Parameters	Volume/Container Material	Preservation Technique	Sample Holding Time
CO_2, CH_4, N_2, O_2 C1-C5 hydrocarbons Helium $\delta^{13}C$ of CO_2 and CH_4 δD of CH_4 C^{14} of CO_2 and CH_4	0.3-L IsoBag Gas Bag®	None	Confirming value with respective laboratory

Table 23. Summary of Sample Containers, Preservation Treatments, and Holding Times for Soil Samples.

Target Parameters	Volume/Container Material	Preservation Technique	Sample Holding Time
Total Organic Carbon (TOC)	4 oz. clear glass jar	Cooled to 4°C	28 days
Percent Moisture	4 oz. clear glass jar	Cooled to 4°C	60 days
Salinity	4 oz. clear glass jar	Cooled to 4°C	6 months

B.3.e. Sample Chain-of-Custody

For CO_2 gas stream samples, a laboratory analysis authorization form will accompany each sample to the designated lab at which point a chain-of-custody follows the sample through the testing processes.

For groundwater, soil gas, and soil samples, the chain-of-custody will be documented using a standardized form. Copies of the form will be provided to the person/lab receiving the samples as well as the person/lab transferring the samples. All the forms will be retained and archived to allow simplified tracking of sample status. The chain-of-custody form and the record-keeping task are the responsibilities of the groundwater, soil gas, and soil sampling personnel.

B.4. Analytical Methods

Discussion in this section appies to physical samples and does not apply to logging, seismic

monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring.

B.4.a. Analytical SOPs

Analytical SOPs for groundwater, soil gas, and soil are referenced in Tables 4, 10, and 11, respectively. If needed, other laboratory-specific SOPs will be determined after a contract with the selected laboratory has been established. Upon request Louisiana Green Fuels can provide all SOPs implemented for specific parameters using appropriate standard methods. Each laboratory technician conducting the analyses on the samples will be trained on the SOP developed for each standard method. Louisiana Green Fuels will include the technician's training certification with the semi-annual report.

B.4.b. Equipment/Instrumentation Needed

Equipment and instrumentation are specified for all analytical methods referenced in Tables 4, 10, and 11.

B.4.c. Method Performance Criteria

Method performance criteria will be designated once the third-party analytical laboratory is selected and contracted, based on their quality assurance and quality control specifications.

B.4.d. Analytical Failure

Each laboratory conducting the analyses listed in Table 4, 10, and 11 will be responsible for appropriately addressing analytical failure according to the SOPs.

B.4.e. Sample Disposal

Each laboratory conducting the analyses listed in Table 4, 10, and 11 will be responsible for appropriate sample disposal according to the SOPs.

B.4.f. Laboratory Turnaround

Laboratory turnaround may vary by laboratory, but generally turnaround of verified analytical results within one month will be suitable for project needs.

B.4.g. Method Validation for Nonstandard Methods

Nonstandard methods are not anticipated for this project. If nonstandard methods are needed or proposed in the future, the USEPA and CARB will be consulted on additional appropriate actions to be taken.

B.5. Quality Control

Discussion in this section appies to physical samples. Seismic monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring do not apply to this section. For logging quality control, refer to the Schlumberger Wireline Log Quality Control Reference Manual (LQCRM), for example (or the manual used by the selected logging vendor). The Wireline Log Quality Control Reference Manual (LQCRM) is used by Schlumberger (Attachment 1). It concisely provides information for the acquisition of high-quality data at the wellsite and its delivery within defined standards. The LQCRM also facilitates the validation of Schlumberger wireline logs at the wellsite or in the office.

B.5.a. QC activities

Blanks

For shallow groundwater sampling, field blanks will be collected and analyzed for the inorganic analytes listed in Table 4 at a frequency of 10% or greater. Blanks will also be collected for deep groundwater baseline sampling and analyzed for the inorganic analytes listed in Table 4 at a frequency of 10% or greater. Field blanks will be exposed to the same field (equipment) and transport (trip) conditions as the groundwater samples. Blanks will be used to detect contamination resulting from the collection and transportation processes. No collection of field blanks is required for soil gas or soil sampling.

Duplicates

For each shallow groundwater and soil gas sampling round, duplicate samples will be collected from a designated well and soil gas probe site, respectively, on a rotating schedule. Duplicate samples will be collected from the same source immediately after (i.e., groundwater) or during i.e., soil gas) the original sample in different containers and processed as all the other samples. Duplicate samples will be used to assess sample heterogeneity and analytical precision.

One duplicate for every 10 soil samples will be collected during the single proposed soil sampling event occurring concurrently will soil gas probe installation.

B.5.b. Exceeding Control Limits

If the groundwater sample analytical results exceed control limits (i.e., ion balances > ±10%), further examination of the analytical results will be done by evaluating the ratio of the measured total dissolved solids (TDS) to the calculated TDS (i.e., mass balance) per APHA method. The method indicates which ion analyses should be considered suspect based on the mass balance ratio. Suspect ion analyses will be then reviewed in the context of historical data and interlaboratory results, when available. Suspect ion analyses will be brought to the attention of the analytical laboratory for confirmation and/or reanalysis. The ion balance will be recalculated, and if the error is still not resolved, suspect data will be identified and potentially given less importance in data interpretations.

B.5.c. Calculating Applicable QC Statistics

Charge Balance

The analytical results will be evaluated to determine the correctness of the analyses based on anion-cation charge balance calculations. Because all potable waters are electrically neutral, the chemical analyses should yield equally negative and positive ionic activity. The anion-cation charge balance will be calculated using the following formula:

$$\%\, difference = 100 \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \qquad \text{(Equation 1)}$$

where the sums of the ions are represented in milliequivalents (meq) per liter and the criteria for acceptable charge balance is ±10%.

Mass Balance

The ratio of the measured TDS to the calculated TDS will be calculated in instances where the charge balance acceptance criteria are exceeded using the following formula:

$$1.0 < \frac{Measured\ TDS}{Calculated\ TDS} < 1.2. \qquad \text{(Equation 2)}$$

Outliers

The determination of one or more statistical outliers is essential prior to the statistical evaluation of groundwater samples. This project will use the USEPA's Unified Guidance (March 2009) as a basis for selection of recommended statistical methods to identify outliers in groundwater chemistry datasets as appropriate. These techniques include Probability Plots, Box Plots, Dixon's test, and Rosner's test. The EPA-1989 outlier test may also be used as another screening tool to identify potential outliers.

B.6. Instrument/Equipment Testing, Inspection, and Maintenance

Discussion in this section appies to physical samples and does not apply to logging, seismic monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring. Logging tool equipment will be maintained as per industry best practices (see For logging quality control, refer to the Schlumberger Wireline Log Quality Control Reference Manual (LQCRM), for example (or the manual used by the selected logging vendor).

For groundwater, soil gas, and soil sampling, field equipment will be maintained, factory-serviced, and factory-calibrated per manufacturer's recommendations. Spare parts that may be needed during sampling will be included in supplies available on-hand during field sampling.

For all laboratory equipment, testing, inspection, and maintenance will be the responsibility of the analytical laboratory per standard practices, method-specific protocols, or NELAP requirements.

B.7. Instrument/Equipment Calibration and Frequency

Discussion in this section appies to physical samples and does not apply to logging, seismic monitoring, pressure/temperature monitoring, atmospheric monitoring, and ecosystem stress monitoring.

B.7.a. Calibration and Frequency of Calibration

Pressure/temperature gauge calibration information is located in Table 13 to Table 18. Logging tool calibration will be at the discretion of the service company providing the equipment, following standard industry practices provided in the Schlumberger Wireline Log Quality Control Reference

Manual (LQCRM), for example (or the manual used by the selected logging vendor). Calibration frequency will also be determined by standard industry practices.

For groundwater sampling, portable field meters or multiprobe sondes used to determine field parameters (e.g., pH, temperature, specific conductance, and dissolved oxygen) are calibrated according to manufacturer recommendations and equipment manuals (Hach, 2006) each day before sample collection begins. Recalibration is performed if any components yield atypical values or fail to stabilize during sampling.

No calibration of field sampling equipment for soil gas or soil is required.

B.7.b. Calibration Methodology

Logging tool calibration methodology will follow standard industry practices as noted in the Schlumberger Wireline Log Quality Control Reference Manual (LQCRM), for example (or the manual used by the selected logging vendor).

For groundwater sampling, standards used for calibration are typically 7 and 10 for pH, a potassium chloride solution yielding a value of 1,413 microsiemens per centimeter (µS/cm) at 25°C for specific conductance, and a 100% dissolved O_2 solution for dissolved oxygen. Calibration is performed for pH meters per manufactuer's specifications using a 2-point calibration bounding the range of the sample. For coulometry, sodium carbonate standards (typically yielding a concentration of 4,000 mg CO_2/L) are routinely analyzed to evaluate instrument.

No calibration of field sampling equipment for soil gas or soil is required.

B.7.c. Calibration Resolution and Documentation

Logging tool calibration resolution and documentation will follow standard industry practices as noted in the Schlumberger Wireline Log Quality Control Reference Manual (LQCRM), for example (or the manual used by the selected logging vendor)..

For groundwater sampling, calibration values are recorded in daily sampling records and any discrepancies in calibration are noted. For parameters where calibration is not acceptable, redundant equipment may be used to ensure that loss of data is minimized.

No calibration of field sampling equipment for soil gas or soil is required.

B.8. Inspection/Acceptance for Supplies and Consumables

B.8.a/b. Supplies, Consumables, and Responsibilities

Supplies and consumables for field and laboratory operations will be procured, inspected, and accepted as required from vendors approved by Louisiana Green Fuels or the respective subcontractor responsible for the data collection activity. Acquisition of supplies and consumables related to groundwater, soil gas, and soil analyses will be the responsibility of the laboratory per established standard methodology or operating procedures.

B.9. Nondirect Measurements

B.9.a. Data Sources

For time-lapse seismic surveys, repeatability is paramount for accurate differential comparison. Therefore, to ensure survey quality, the locations of the shots and the acquisition methodology of sequential surveys will remain consistent. Once the surveys are conducted, they will be compared to a baseline survey to track and monitor the plume development.

B.9.b. Relevance to Project

Time-lapse seismic surveys will be used to track changes in the CO_2 plume propagation in the subsurface. Processing and comparing subsequent surveys to a baseline will allow project managers to monitor plume growth, as well as to ensure that the plume does not move outside of the intended Storage Complex. Numerical modeling will be used to predict the CO_2 plume growth and migration over time by combining the processed seismic data with the existing geologic model. In-zone pressure monitoring data will also be used in numerical modeling to predict the plume and pressure front behavior and confirm the plume stage within the AOR.

B.9.c. Acceptance Criteria

Following standard industry practices will ensure that the gathered seismic data are used for accurate modeling and monitoring. Similar ground conditions, shot points located within tolerable limits, functional geophones, and similar seismic input signal will be used from survey to survey to ensure repeatability. To the extent possible, source stations my be fabricated concrete pads that

can be periodically reoccupied. This will ensure consistent signal generation stations for the project.

When processing seismic data, several quality assurance checks will be performed in accordance with industry standards, including reformatting to Omega structured files, geometry application, amplitude compensation, predictive deconvolution, elevation statics correction, root mean square (RMS) amplitude gain, velocity analysis every 2 km, normal move out (NMO) application using picked velocities, common mid-point (CMP) stacking, random noise attenuation, and instantaneous gain.

B.9.d. Resources/Facilities Needed

Louisiana Green Fuels will subcontract all necessary resources and facilities for seismic monitoring, in-zone pressure monitoring, and groundwater sampling.

B.9.e. Validity Limits and Operating Conditions

For seismic surveys and numerical modeling, intraorganizational checks between trained and experienced personnel will ensure that all surveys and numerical modeling are conducted conforming to standard industry practices.

B.10. Data Management

B.10.a. Data Management Scheme

Louisiana Green Fuels or a designated contractor will maintain the required project data as provided in the permit. Data will be backed up on tape or held on secure servers.

B.10.b. Recordkeeping and Tracking Practices

All records of gathered data will be securely held and properly labeled for auditing purposes.

B.10.c. Data Handling Equipment/Procedures

All equipment used to store data will be properly maintained and operated according to proper industry techniques. Louisiana Green Fuels IT system and vendor data acquisition systems will interface with one another and all subsequent data will be held on a secure server.

B.10.d. Responsibility

The primary project managers will be responsible for ensuring proper data management is maintained.

B.10.e. Data Archival and Retrieval

All data will be held by Louisiana Green Fuels, maintained and stored for auditing purposes as described in Section B.10.a.

B.10.f. Hardware and Software Configurations

All Louisiana Green Fuels and vendor hardware and software configurations will be appropriately interfaced.

B.10.g. Checklists and Forms

Checklists and forms will be procured and generated as necessary.

C. ASSESSMENT AND OVERSIGHT

C.1. Assessments and Response Actions

C.1.a. Activities to be Conducted

Refer to Table 1 in Section A.3.a/b for the summary of testing and monitoring to be performed.

Groundwater quality, atmospheric, ecosystem stress, and soil gas composition data will be collected at the frequency outlined in the table. Soil samples will only be collected suring soil gas probe installation during the pre-injection phase to establish site soil characteristics. After completion of the sample analyses, the results will be reviewed for QC criteria as noted in Section B.5. If the data quality fails to meet the criteria set in Section B.5, the samples will be reanalyzed, if within holding time criteria. If outside of holding time criteria, additional samples may be collected or sample results may be excluded from data evaluations and interpretations. Evaluation for data consistency will be performed according to procedures described in the USEPA 2009 Unified Guidance (USEPA, 2009).

C.1.b. Responsibility for Conducting Assessments

Organizations gathering data will be responsible for conducting their internal assessments. All stop work orders will be handled internally within individual organizations.

C.1.c. Assessment Reporting

All assessment information should be reported to the project managers of the individual organizations outlined in Section A.1.a/b.

C.1.d. Corrective Action

All corrective action affecting only an individual organization's data collection responsibility should be addressed, verified, and documented by the individual project managers and communicated to the other project managers as necessary. Corrective actions affecting multiple organizations should be addressed by all members of the project leadership and communicated to other members on the distribution list stated for the QASP. Assessments may require integration of information from multiple monitoring sources across several organizations (operational, in-zone monitoring, and above-zone monitoring) to determine whether correction actions are required

and/or the most cost-efficient and effective action to implement. Louisiana Green Fuels will coordinate multiorganization assessments and corrective actions as warranted.

C.2. Reports to Management

C.2.a/b. QA status Reports

Quality assurance status reports should not be needed. However, if any testing or monitoring techniques are changed, the QASP will be reviewed and updated as appropriate in consultation with USEPA and CARB. Revised QASPs will be distributed by Louisiana Green Fuels to the full distribution list provided at the beginning of this document.

D. Data Validation and Usability

D.1. Data Review, Verification, and Validation

D.1.a. Criteria for Accepting, Rejecting, or Qualifying Data

Groundwater quality, soil gas composition, and soil quality data validation will include the review of the concentration units and sample holding times, and the review of duplicates, blanks, and other appropriate QA/QC results. All groundwater quality, soil gas composition, and soil quality results will be entered into a database or spreadsheet with periodic data review and analysis. Louisiana Green Fuels will retain copies of the laboratory analytical test results and/or reports. Analytical results will be reported on the frequency based on the approved UIC permit conditions. In the periodic reports, data will be presented in graphical and tabular formats as appropriate to characterize general groundwater quality and identify intrawell variability with time. After sufficient data have been collected, additional methods, such as those described in the USEPA 2009 Unified Guidance (USEPA, 2009), will be used to evaluate intrawell or inrtaprobe variations for groundwater and soil gas constituents, respectively, and if significant changes have occurred that could be the result of CO_2 or brine seepage beyond the intended storage reservoir.

D.2. Verification and Validation Methods

D.2.a. Data Verification and Validation Processes

See Sections B.5 and D.1.a.

Appropriate statistical software will be used to determine data consistency.

D.2.b. Data Verification and Validation Responsibility

Louisiana Green Fuels or its designated subcontractor will verify and validate groundwater, soil gas, and soil sampling data.

D.2.c. Issue Resolution Process and Responsibility

Louisiana Green Fuels or its designated coordinator will oversee the groundwater, soil gas, and soil data handling, management, and assessment process. Staff involved in these processes will consult with the coordinator to determine actions required to resolve any possible issues.

D.2.d. Checklist, Forms, and Calculations

Checklists and forms will be developed to meet specific permit requirements.

D.3. Reconciliation with User Requirements

D.3.a. Evaluation of Data Uncertainty

Statistical software will be used to determine groundwater, soil gas, and soil data consistency using methods consistent with USEPA 2009 Unified Guidance (USEPA, 2009).

D.3.b. Data Limitations Reporting

The organization-level project managers will be responsible for ensuring that data developed by their respective organizations is presented with the appropriate data-use limitations.

Louisiana Green Fuels will use the current operating procedure for utilizing, sharing, and presenting results and/or data for the Louisiana Green Fuels project. The procedure has been developed to ensure quality and internal consistency, and facilitate tracking and record keeping of data end users and associated publications.

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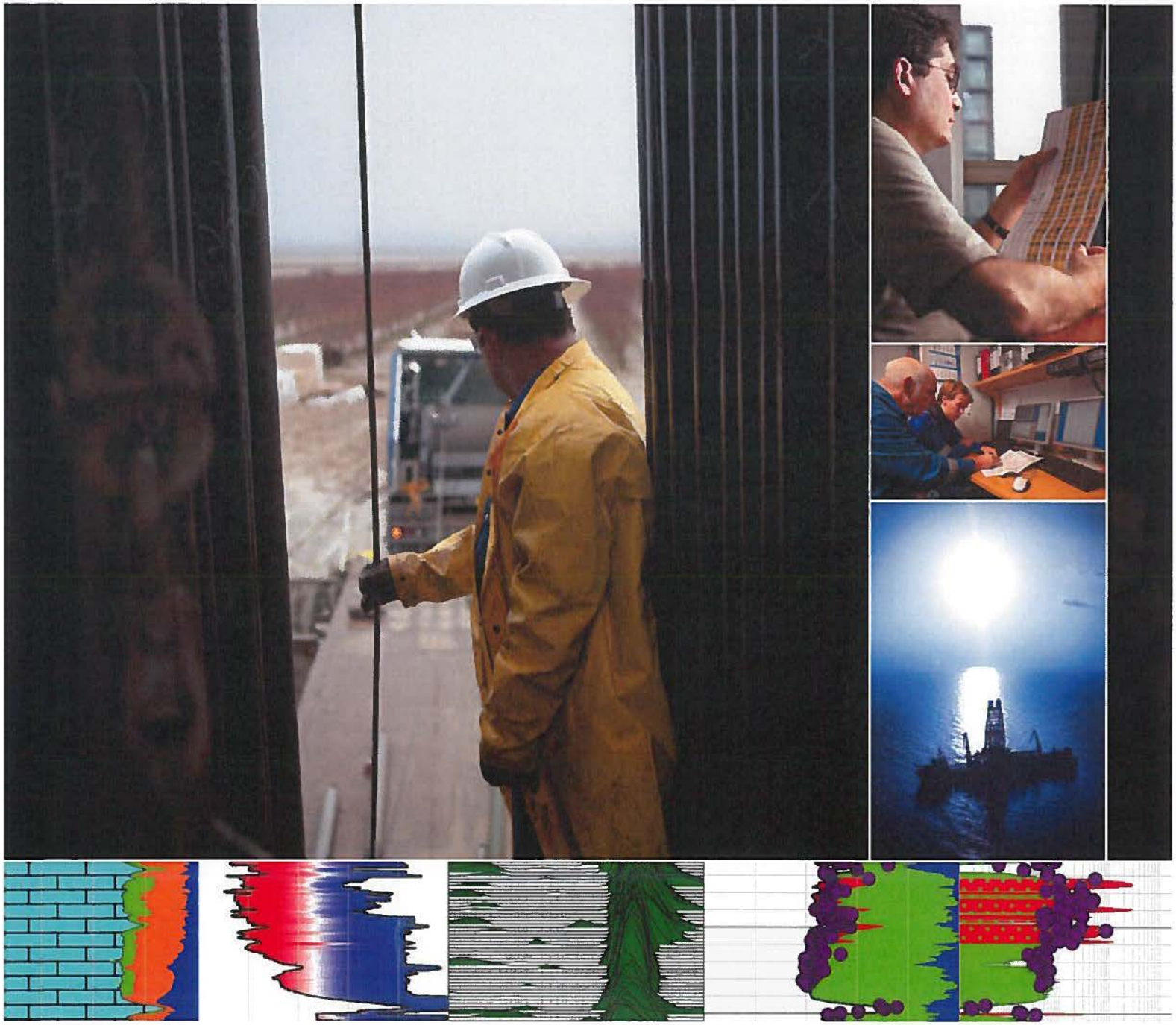
ATTACHMENT 1

SCHLUMBERGER WIRELINE LOG QUALITY CONTROL REFERENCE MANUAL

Schlumberger

Wireline Log Quality Control Reference Manual



Schlumberger

Wireline Log Quality Control Reference Manual

Schlumberger
3750 Briarpark Drive
Houston, Texas 77042

www.slb.com

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11-FE-0131

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Foreword

The certification of acquired data is an important aspect of logging. It is performed through the observation of quality indicators and can be completed successfully only when a set of specified requirements is available to the log users.

This Log Quality Control Reference Manual (LQCRM) is the third edition of the log quality control specifications used by Schlumberger. It concisely provides information for the acquisition of high-quality data at the wellsite and its delivery within defined standards. The LQCRM is distributed to facilitate the validation of Schlumberger wireline logs at the wellsite or in the office.

Because the measurements are performed downhole in an environment that cannot be exhaustively described, Schlumberger cannot and does not warrant the accuracy, correctness, or completeness of log data.

Large variations in well conditions require flexibility in logging procedures. In some cases, important deviations from the guidelines given here may occur. These deviations may not affect the validity of the data collected, but they could reduce the ability to check that validity.

Catherine MacGregor
President, Wireline

Introduction

Data is a permanent asset of energy companies that may be used in unforeseen ways. Schlumberger is committed to and accountable for managing and delivering quality data. The quality of the data is the cornerstone of Schlumberger products and services.

Data quality

Quality is conformance to predefined standards with minimum variation. This document defines the standards by which the quality of the data of Schlumberger wireline logs is determined. The attributes that form the data quality model are

- accuracy
- repeatability
- integrity
- traceability
- timeliness
- relevance
- completeness
- sufficiency
- interpretability
- reputation
- objectivity
- clarity
- availability
- accessibility
- security.

Accuracy

Accuracy is how close to the true value the data is within a specified degree of conformity (e.g., metrology and integrity). Accuracy is a function of the sensor design; the measurement cannot be made more accurate by varying operating techniques, but it can fail to conform to the defined accuracy as a result of several errors (e.g., incorrect calibration).

Repeatability

Repeatability of data is the consistency of two or more data products acquired or processed using the same system under the same conditions. Reproducibility, on the other hand, is the data consistency of two or more data products acquired or processed using different systems or under different conditions. The majority of wireline measurements have a defined repeatability range, which is applicable only when the measurement is conducted under the same conditions. Repeatability is used to validate the measurement acquired during the main logging pass, as well as identify anomalies that may arise during the survey for relogging.

Integrity

The integrity of data is essential for the believability of data. Data with integrity is not altered or tampered with. There are situations in which data is altered in a perfectly acceptable manner (e.g., applying environmental corrections, using processing parameters for interpretation). Any such changes, which involve an element of judgment, are not done to intentionally produce results inconsistent with the measurements or processed data and are to the best and unbiased judgment of the interpreter. Results of interpretation activities are auditable, clearly marked, and traceable.

Traceability

Traceability of data refers to having a complete chain defining a measurement from its point of origin (sensor) to its final destination (formation property). At each step of the chain, appropriate measurement standards are respected, well documented, and auditable.

Timeliness

Timeliness is the availability of the data at the time required. Timeliness ensures that all tasks in the process of acquiring data are conducted within the time window defined for such tasks (e.g., wellsite calibrations and checks are done within the time window defined).

Relevance

Relevance is the applicability and helpfulness of the acquired dataset within the business context (e.g., selection of the right service for the well conditions). Most services have a defined operating envelope in which the measurement is considered valid. Measurements conducted outside their defined envelope, although the measurement process may have been completed satisfactorily, are almost always irrelevant (e.g., recording an SP curve in an oil-base mud environment).

Completeness

Completeness ensures that the data is of sufficient breadth, depth, and scope to meet predefined requirements. This primarily means that all required measurements are available over the required logging interval, with no missing curves or gaps in curves over predefined required intervals of the log.

Sufficiency

Sufficiency ensures that the amount of data that is acquired or processed meets the defined objectives of the operation. For example, when the defined objective is to compute the hole volume of an oval hole, a four-arm caliper service—at minimum—must be used. Using a single-arm caliper service would not provide sufficient information to achieve the defined objective and would inadvertently result in overestimation of the hole volume.

Interpretability

Interpretability of data requires that the measurement is specified in appropriate terminology and units and that the data definitions are clear and documented. This is essential to ensure the capability of using the data over time (i.e., reusability).

Reputation

Reputation refers to data being trusted or highly regarded in terms of its source, content, and traceability.

Objectivity

The objectivity of data is an essential attribute of its quality, unbiased and impartial, both at acquisition and at reuse.

Clarity

Clarity refers to the availability of a clear, unique definition of the data by using a controlled data dictionary that is shared. For example, when "NPHI" is referred to, it must be understood by all that NPHI is the thermal neutron porosity in porosity units (m^3/m^3 or ft^3/ft^3), computed from a thermal neutron ratio that is calibrated using a single-point calibration mechanism (gain only), and is the ratio of counts from a near and a far receiver, with the counts corrected only for hole size and not corrected for detector dead time.

Clarity ensures objectivity and interpretability over time.

Availability

Availability of data ensures the distribution of data only to the intended parties at the requested time (i.e., no data is disclosed to any other party than the owner of the data without prior written permission).

Accessibility

Accessibility ensures the ease of retrievability of data using a classification model. Wireline data are classified into three datasets:

- Basic dataset is a limited dataset suitable for quicklook interpretation and transmission of data.
- Customer dataset consists of a complete set of data suitable for processing (measurements with their associated calibrations), recomputing (raw curves), and validating (log quality control [LQC] curves) the measurements of the final product delivered. The customer dataset includes all measurements required to fully reproduce the data product with a complete and auditable traceability chain.
- Producer dataset includes Schlumberger-proprietary data, which are meaningful only to the engineering group that supports the tool in question (e.g., the 15th status bit of ADC015 on board EDCIB023 in an assembly).

Security

The security of data is essential to maintain its confidentiality and ensure that data files are clean of malware or viruses.

Calibration theory

The calibration of sensors is an integral part of metrology, the science of measurement. For most measurements, one of the following types of calibrations is employed:

- single-point calibration
- two-point calibration
- multiple-point calibration.

Because most measurements operate in a region of linear response, any two points on the response line can be compared with their associated calibration references to determine a gain and an offset (two-point calibration) or a gain (single-point calibration). The gain and offset values are used in the calibration value equation, which converts any measured value to its associated calibrated value.

There are three events that measurements may have one or more of:

- Master calibration: Performed at the shop on a quarterly or monthly basis, a master calibration usually comprises a primary measurement done to a measurement standard and a reference measurement that serves as a baseline for future checks. The primary measurement is the calibration of the sensor used for converting a raw measurement into its final output.
- Wellsite before-survey calibration or check: Measurements that have a master calibration are normally not calibrated at the wellsite; rather, the reference measurement conducted in the master calibration is repeated at the wellsite before conducting the survey to ensure that the tool response has not changed. Measurements that do not have a master calibration may employ a wellsite calibration that is conducted prior to starting the survey.
- Wellsite after-survey check: Some measurements employ an after-survey check (optional for most measurements) to ensure that the tool response has not changed from before the survey.

All such events are recorded in a calibration summary listing (CSL) (Fig. 1).

The calibration summary listing contains an auditable trail of the event:

- equipment with serial numbers
- actual measurement and the associated range (minimum, nominal, and maximum)
- time the event was conducted.

For the event to be valid, the measurement must fall within the defined minimum and maximum limits, using the same equipment (verified through the mnemonics and serial numbers), and performed on time (verified through the time stamp on the summary listing).

More details on the calibrations associated with the wide range of Schlumberger wireline measurements are in the *Logging Calibration Guide*, which is available through your local Schlumberger representative.

Hostile Natural Gamma Ray Sonde / Equipment Identification

Primary Equipment:	
HNGS Sonde	HNGS - BA
Auxiliary Equipment:	
HNGS Sonde Housing	HNSH - BA
Gamma Source Radioactive	GSR - U

Hostile Natural Gamma Ray Sonde Master Calibration
Detector 1 Calibration

Phase	Na 511 Peak Set Point	Value	Phase	Th Peak Loc	Value	Phase	Th Peak Res %	Value
Master		42.00	Master		211.9	Master		7.396
38.00 (Minimum)	40.00 (Nominal)	42.00 (Maximum)	201.0 (Minimum)	209.6 (Nominal)	218.3 (Maximum)	5.000 (Minimum)	7.000 (Nominal)	9.000 (Maximum)
Phase	Background Count Rate CPS	Value	Phase	Gain Ratio	Value			
Master		96.67	Master		0.9936			
20.00 (Minimum)	142.5 (Nominal)	265.0 (Maximum)	0.9400 (Minimum)	1.000 (Nominal)	1.060 (Maximum)			

Master:

Hostile Natural Gamma Ray Sonde Master Calibration
Detector 2 Calibration

Phase	Na 511 Peak Set Point	Value	Phase	Th Peak Loc	Value	Phase	Th Peak Res %	Value
Master		41.00	Master		211.1	Master		6.985
38.00 (Minimum)	40.00 (Nominal)	42.00 (Maximum)	201.0 (Minimum)	209.6 (Nominal)	218.3 (Maximum)	5.000 (Minimum)	7.000 (Nominal)	9.000 (Maximum)
Phase	Background Count Rate CPS	Value	Phase	Gain Ratio	Value			
Master		96.01	Master		1.017			
20.00 (Minimum)	142.5 (Nominal)	265.0 (Maximum)	0.9400 (Minimum)	1.000 (Nominal)	1.060 (Maximum)			

Master:

Figure 1. Example of a master calibration.

*Mark of Schlumberger
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Depth Control and Measurement

Overview

Depth is the most fundamental wireline measurement made; therefore, it is the most important logging parameter. Because all wireline measurements are referenced to depth, it is absolutely critical that depth is measured in a systematic way, with an auditable record to ensure traceability.

Schlumberger provides through its wireline services an absolute depth measurement and techniques to apply environmental corrections to the measurement that meet industry requirements for subsurface marker referencing.

The conveyance of tools and equipment by means of a cable enables the determination of an absolute wellbore depth under reasonable hole conditions through the strict application of wellsite procedures and the implementation of systematic maintenance and calibration programs for measurement devices. The essentials of the wireline depth measurement are the following:

- Depth is measured from a fixed datum, termed the depth reference point, which is specified by the client.
- The Integrated Depth Wheel (IDW) device (Fig. 1) provides the primary depth measurement, with the down log taken as the correct depth reference.
- Slippage in the IDW wheels is detected and automatically compensated for by the surface acquisition system.
- The change in elastic stretch of the cable resulting from changing direction at the bottom log interval is measured and applied to the log depth as a delta-stretch correction.
- Other physical effects on the cable in the borehole, including changes in length owing to wellbore profile, temperature, and other hole conditions, are not measured but can be corrected for after logging is complete.
- Subsequent logs that do not require a primary depth measurement are correlated to a reference log specified by the client, provided that enough information exists to validate the correctness of the depth measured on previous logs.
- Traceability of the corrections applied should be such that recovery of absolute depth measurements is possible after logging, if required.

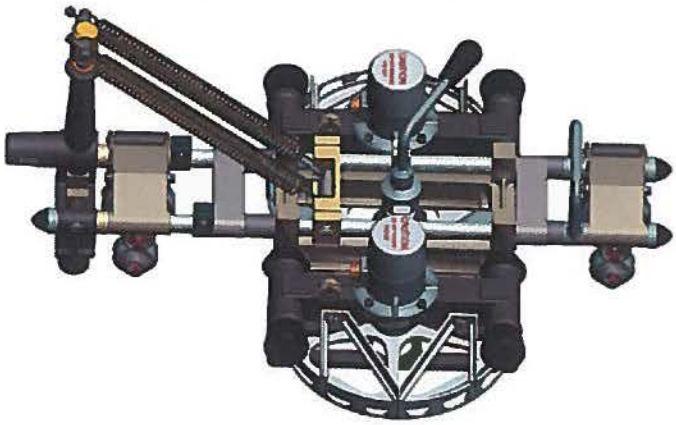

Figure 1. Integrated Depth Wheel device.

By strict application of this procedure, Schlumberger endeavors to deliver depth measurement with an accuracy of ±5 ft per 10,000 ft and repeatability of ±2 ft per 10,000 ft [±1.5 m and ±0.6 m per 3,050 m, respectively] in vertical wells.

Specifications

Measurement Specifications	
Accuracy	±5 ft per 10,000 ft [±1.5 m per 3,050 m]
Repeatability	±2 ft per 10,000 ft [±0.6 m per 3,050 m]

Calibration

The IDW calibration must be performed every 6 months, after 50 wellsite trips, or after 500,000 ft [152,400 m] have passed over the wheel, whichever comes first. The IDW device is calibrated with a setup that is factory-calibrated with a laser system, which provides traceability to international length standards.

Tension devices are calibrated every 6 months for each specific cable by using a load cell.

For more information, refer to the *Logging Calibration Guide*, which is available through your local Schlumberger representative.

The high-precision IDW device uses two wheels that measure cable motion at the wireline unit. Each wheel is equipped with an encoder, which generates an event for every 0.1 in [0.25 cm] of cable travel. A wheel correction is applied to obtain the ideal of one pulse per 0.1 in of cable travel.

Integration of the pulses results in the overall measured depth, which is the distance measured along the actual course of the borehole from the surface reference point to a point below the surface.

A tension device, commonly mounted on the cable near the IDW device, measures the line tension of the cable at the surface.

Depth control procedure

On arrival at the wellsite, the wireline crew obtains all available information concerning the well and the depth references (wellsite data) from the client's representative. Information related to the calibrations of the IDW device and the tension device is entered in the surface acquisition system.

First trip

First log

The procedure for the first log in a well consists of the following major steps:

1. Set up the depth system, and ensure that wheel corrections are properly set for each encoder.
2. Set tool zero (Fig. 2) with respect to the client's depth reference.
3. Measure the rig-up length (Fig. 3) between the IDW device and the rotary table at the surface. Investigate, and correct as necessary, any significant change in the rig-up length from that measured with the tool close to the surface.
4. Run in the hole with the toolstring.
5. Measure the rig-up length (Fig. 3) between the IDW device and the rotary table at bottom.
6. Correct for the change in elastic stretch resulting from the change in cable or tool friction when logging up.
7. Record the main log.
8. Record one or more repeat sections for repeatability analysis.†
9. Pull the toolstring out of the hole and check the depth on return to surface.

To set tool zero on a land rig, fixed platform, or jackup, the toolstring is lowered a few feet into the hole and then pulled up, stopping when the tool reference is at the client's depth reference point (Fig. 2).

Figure 2. Tool zero.

†Operational considerations may dictate a change in the order of Steps 6–8.

The following procedure for setting tool zero is used on floating vessels, semisubmersible rigs, and drillships equipped with a wave motion compensator (WMC):

1. With the WMC deactivated, stop the tool reference at the rotary table, and set the system depth to zero.
2. Lower the tool until the logging head is well below the riser slip joint, then flag the cable at the rotary table and record the current depth.
3. Have the driller pull up slowly on the elevators, until the WMC is stroking about its midpoint.
4. Raise or lower the tool until the cable flag is back at the rotary table.
5. Set the system depth to the depth recorded in Step 2.

Measuring the cable rig-up length ensures that the setup has not changed while running in the well (e.g., slack in the logging cable, movement of the logging unit, the blocks, or the sheaves). The following procedure is used to measure the rig-up length of the cable (Fig. 3):

1. Run in the hole about 100 ft [30 m], flag the cable at the IDW device, and note the depth.
2. Lower the toolstring until the flag is at the rotary table. Subtract the depth recorded in Step 1 from the current depth. The result is the rig-up length at surface (RULS).
3. Record RULS.

The speed used to proceed in the hole should avoid tool float (caused by excessive force owing to mud viscosity acting on the tool) or birdcaging of the cable. To the extent possible and operational considerations permitting, a constant speed should be maintained while running downhole. At the bottom of the hole, the measurement process is conducted to obtain the rig-up length at bottom (RULB), which is also recorded. If RULB differs from RULS by more than 1 ft [0.3 m], the rig-up has changed and the cause of the discrepancy must be investigated and eliminated or corrected for.

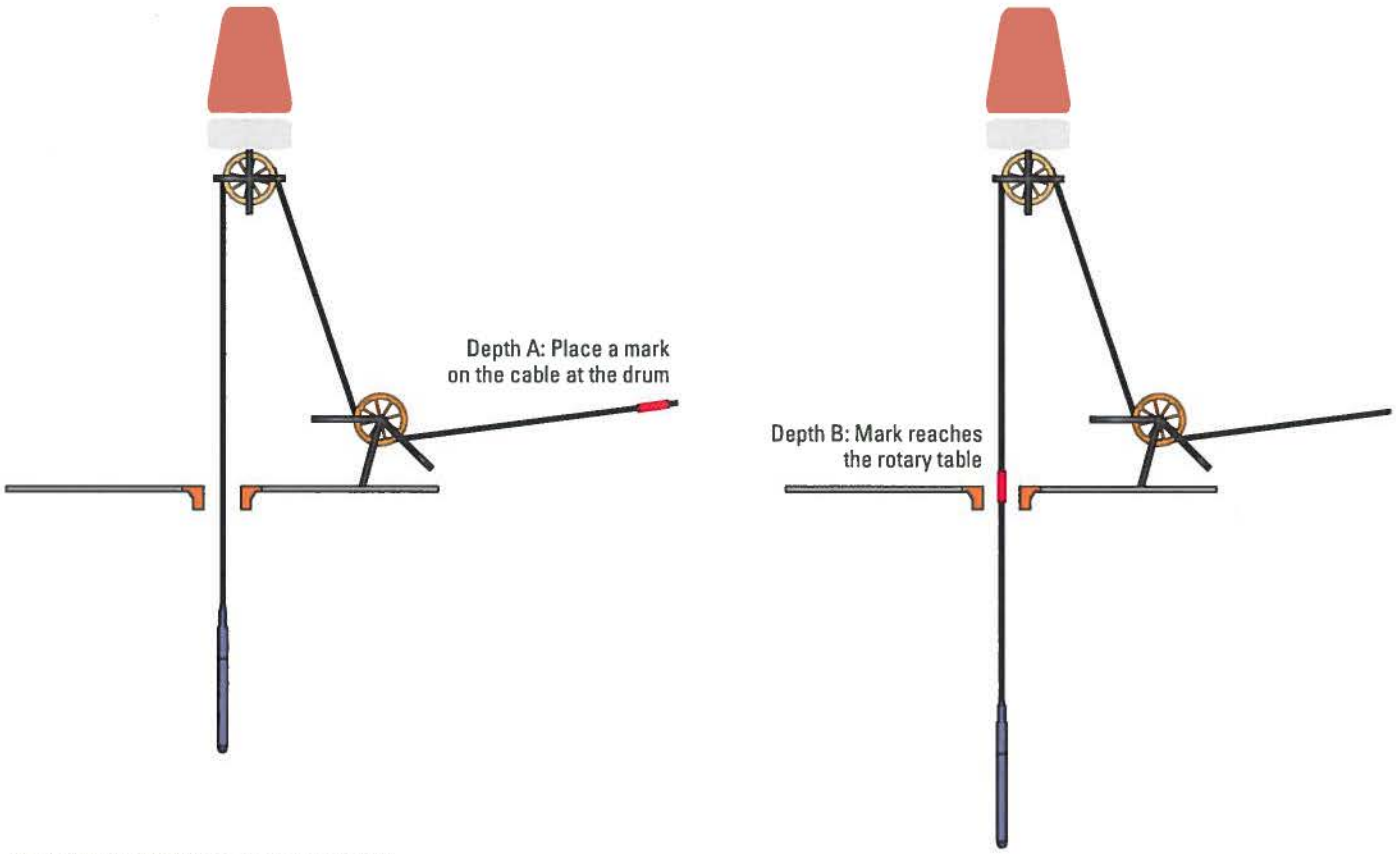

Figure 3. Rig-up length measurement procedure.

The rig-up length correction (RULC = RULS – RULB) is applied by adding RULC to the system depth. RULC is recorded in the Depth Summary Listing (Fig. 5).

To correct for the change of elastic stretch, the log-down/log-up method (Fig. 4) is applied as close as is reasonable to the bottom log interval:

1. Continue toward the bottom of the well at normal speed.
2. Log down a short section (minimum 200 ft [60 m]) close to the bottom, making sure to include distinctive formation characteristics for correlation purposes.
3. At the bottom, open calipers (if applicable) and log up a section overlapping the down log obtained in Step 2.
4. Using the down log as a reference, adjust the up-log depth to match the down log.
5. The adjustment is the stretch correction (SCORR) resulting from the change in tension. SCORR should be added to the hardware depth before logging the main pass.
6. Record SCORR and the depth at which it was determined in the Depth Summary Listing (Fig. 5).

If it is determined to be too risky to apply the delta-stretch correction before starting the log, the log can be recorded with no correction and then depth-shifted after the event with a playback. This procedure must be documented clearly in the Depth Summary Listing remarks. Such a procedure is justified when the well is excessively hot or sticky, and following the steps previously outlined could lead to a significant risk of tool problems or failure to return to bottom (and thus to loss of data).

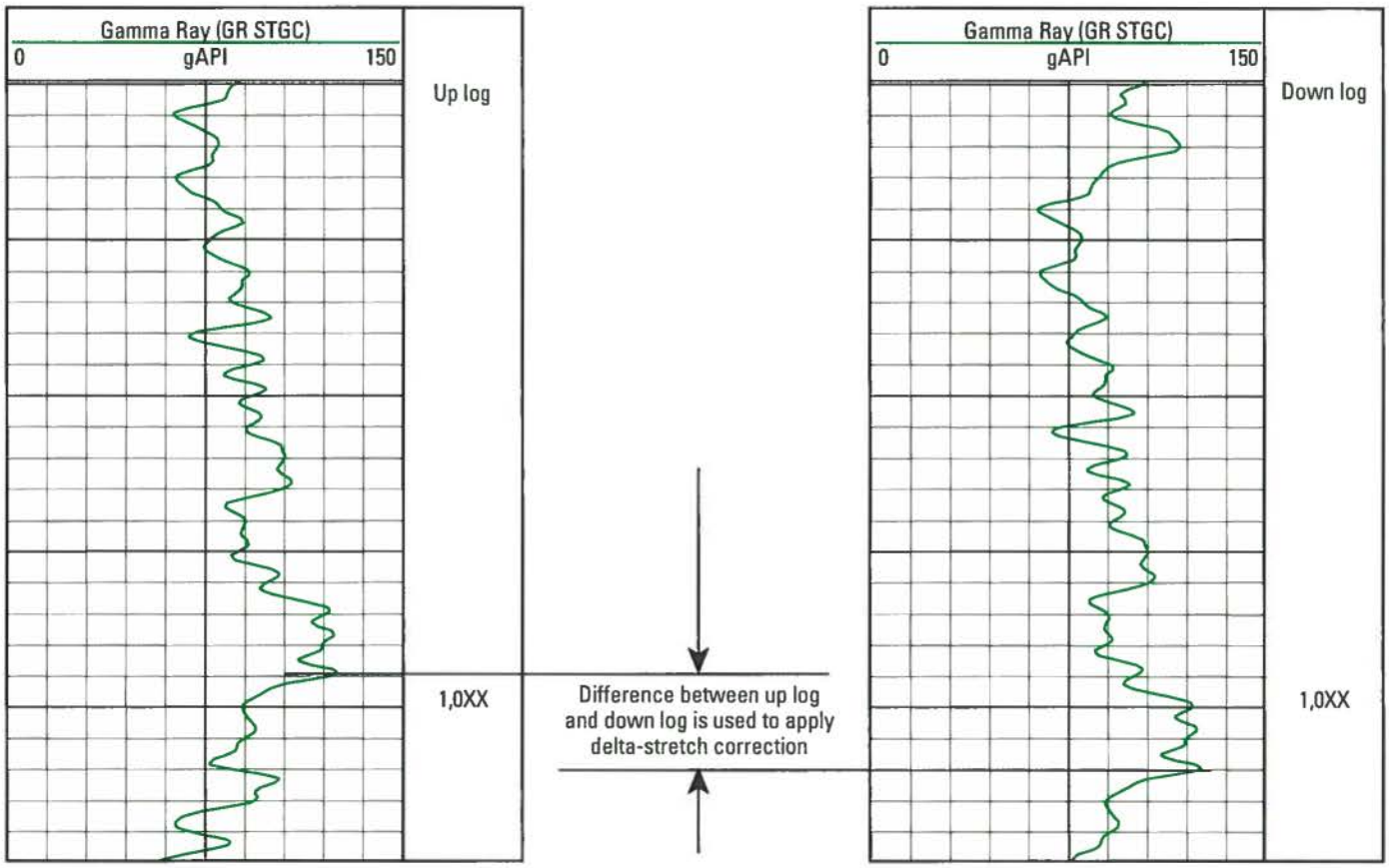

Figure 4. Stretch correction.

After pulling out of the hole, tool zero is checked at the surface, as was done before running in the hole, and the difference is recorded in the Depth Summary Listing (Fig. 5). In deviated wells in particular, environmental effects may lead to a re-zero error, with the depth system reading other than zero when the tool reference is positioned opposite the log reference point after return to the surface. Recording this difference is an essential step in controlling the quality of any depth correction computed after the log, because that depth correction process should include an estimate of the expected re-zero error.

All information related to the procedure followed for depth control should be recorded in the Depth Summary Listing (Fig. 5) for future reference.

DEPTH SUMMARY LISTING

Date Created: 10-Dec-20XX 12:09:15

Depth System Equipment

Depth Measuring Device		Tension Device		Logging Cable	
Type :	IDW-B	Type :	CMTD-B/A	Type :	7-46P
Serial Number:	4XX	Serial Number:	82XXX	Serial Number:	83XX
Calibration Date:	10-Dec-20XX	Calibration Date:	10-Dec-20XX	Length:	18750 FT
Calibrator Serial Number:	15XX	Calibrator Serial Number:	98XX	Conveyance Method:	Wireline
Calibration Cable Type:	7-46P	Number of Calibration Points:	10	Rig Type:	LAND
Wheel Correction 1:	-3	Calibration RMS:	11		
Wheel Correction 2:	-2	Calibration Peak Error:	15		

Depth Control Parameters

Log Sequence:	First Log in the Well
Rig Up Length At Surface:	352.00 FT
Rig Up Length At Bottom:	351.00 FT
Rig Up Length Correction:	1.00 FT
Stretch Correction:	5.00 FT
Tool Zero Check At Surface:	0.50 FT

Depth Control Remarks

1. Subsequent trip to the well. Downlog correlated to reference log XXX by YYY company dated DD-MM-YYYY.
2. Non-Schlumberger reference log. Full 1st trip to the well depth control procedure applied, which required the addition of XX ft to the down log.
3. Delta-stretch correction was conducted at 12XXX ft and applied to depth prior to recording the main log.
4. Z-chart used as a secondary depth check.

Figure 5. Depth Summary Listing for the first trip, first log in the well.

Subsequent logs

The depth of subsequent logs on the same trip is tied into the first log using the following procedure:

1. Properly zero the tool as for the first log.
2. The rig-up length does not need to be measured if the setup has not changed since the previous log.
3. Match depths with the first log by using a short up-log pass.
4. Run the main log and repeat passes as necessary.
5. Record the re-zero error in the Depth Summary Listing. This is part of the traceability that makes possible the determination of absolute depth after the event, if required.

Subsequent logs should be on depth with the first log over the complete interval logged. However, particularly when toolstrings of different weights are run in deviated wells, the relative depths of the logs can change over long logging intervals. Subsequent correction should enable removing all discrepancies.

The amount and sign of the correction applied and the depth at which it was determined must be recorded in the Depth Summary Listing. For any down log made, the delta-stretch correction should also be recorded, as well as the depth at which it was determined.

All information related to the procedure followed for depth control of subsequent logs of the first trip should be recorded in the Depth Summary Listing (Fig. 6).

DEPTH SUMMARY LISTING

Date Created: 10-Dec-20XX 14:38:50

Depth System Equipment

Depth Measuring Device		Tension Device		Logging Cable	
Type :	IDW-B	Type :	CMTD-B/A	Type :	7-46P
Serial Number:	4XX	Serial Number:	82XXX	Serial Number:	83XX
Calibration Date:	10-Dec-20XX	Calibration Date:	10-Dec-20XX	Length:	18750 FT
Calibrator Serial Number:	15XX	Calibrator Serial Number:	98XX	Conveyance Method:	Wireline
Calibration Cable Type:	7-46P	Number of Calibration Points:	10	Rig Type:	LAND
Wheel Correction 1:	-3	Calibration RMS:	11		
Wheel Correction 2:	-2	Calibration Peak Error:	15		

Depth Control Parameters

Log Sequence:	Subsequent trip In the Well
Reference Log Name:	AIT-GR
Reference Log Run Number:	1
Reference Log Date:	10-Dec-20XX

Depth Control Remarks

1. Subsequent log on 1st trip correlated to first log in the well from XX000 to XX200 ft
2. Speed correction not applied.
3. Z-chart used as a secondary depth check.
4. Correction applied to match reference log = XX ft, determined at depth XXX00 ft.
5. No rigup changes from previous log.

Figure 6. Depth Summary Listing for first trip, subsequent logs.

Subsequent trips

If there is not enough information in the Depth Summary Log from previous trips to ensure that correct depth control procedures have been applied, subsequent trips are treated as a first trip, first log in the well.

If sufficient information from previous trips was recorded to show that correct depth control procedures were applied, the previous logs can be used as a reference. The subsequent trips proceed as if running the initial trip with the following exceptions:

1. In conjunction with the client, decide which previous log to use as the downhole depth reference. Ensure that a valid copy of the reference log is available for correlation purposes. If the depth reference is a wireline log from a oilfield service provider other than Schlumberger, proceed as for the first log in the well, and investigate and document any discrepancies found with respect to the reference log.
2. Run in the hole and record a down log across an overlap section at the bottom of the reference log. If the overlap section is off by less than 5 ft per 10,000 ft, adjust the depth to match the current down log with the reference log. This adjustment ensures that the down section of the current log is using the same depth reference as the correlation log. Record any corrections made as the subsequent trip down log correction.
3. If the overlap log is off by more than 5 ft per 10,000 ft, investigate and resolve any problems. Record any depth discrepancies. Consult with the client to decide which log to use as the depth reference.
4. Run down to the bottom of the well at a reasonable speed so that the tool does not float.
5. Log main and repeat passes, correcting for stretch following the first trip procedure.
6. The logging pass should overlap with the reference log by at least 200 ft, if possible. The depth should match the reference log. Any discrepancies should be noted in the Depth Summary Listing or the log remarks.

All information related to the depth control procedure followed should be recorded in the Depth Summary Listing (Fig. 7).

DEPTH SUMMARY LISTING

Date Created: 10-Dec-20XX 14:26:56

Depth System Equipment

Depth Measuring Device		Tension Device		Logging Cable	
Type :	IDW-B	Type :	CMTD-B/A	Type :	7-46P
Serial Number:	4XX	Serial Number:	82XXX	Serial Number:	83XX
Calibration Date:	10-Dec-20XX	Calibration Date:	10-Dec-20XX	Length:	18750 FT
Calibrator Serial Number:	15XX	Calibrator Serial Number:	9851	Conveyance Method:	Wireline
Calibration Cable Type:	7-46P	Number of Calibration Points:	10	Rig Type:	LAND
Wheel Correction 1:	-3	Calibration RMS:	11		
Wheel Correction 2:	-2	Calibration Peak Error:	15		

Depth Control Parameters

Log Sequence:	Subsequent trip to the well
Reference Log Name:	AIT-GR
Reference Log Run Number:	1
Reference Log Date:	10-Dec-20XX
Subsequent Trip Down Log Correction:	1.00 FT

Depth Control Remarks

1. Subsequent trip to the well.
2. Down pass correlated to reference log within +/- 0.05%.
3. Correlation to reference log performed from XX000 to XX200 ft.
4. Correction applied to match reference log = XX ft, determined at depth XXX00 ft..
5. Z-chart used as a secondary depth check.

Figure 7. Depth Summary Listing for subsequent trips.

Spudding

Spudding is not a recommended procedure, but it is sometimes necessary to get past an obstruction in the borehole. It generally involves making multiple attempts from varying depths or using varying cable speed to get past an obstruction.

If the distance pulled up is small, the error introduced is also small. In many cases, however, the tool is pulled back up for a considerable distance (i.e., increasing cable over wheel) in an attempt to change its orientation. Then, the correction necessary to maintain proper depth control becomes sizeable.

If multiple attempts are made, the correction necessary to maintain proper depth control also becomes sizeable.

When possible, log data is recorded over the interval where spudding occurs in case consequent damage occurs to the equipment that prevents further data acquisition. If it is not possible to pass an obstruction in the well, data is recorded while pulling out of the hole for remedial action.

Absolute depth

Measurements made with wireline logs are often used as the reference for well depth. However, differences are usually noted between wireline depth and the driller's depth. Which one is correct? The answer is neither. For more information, refer to SPE 110318, "A Technique for Improving the Accuracy of Wireline Depth Measurements."

Wireline depth measurement is subject to environmental corrections that vary with many factors:

- well profile
- mud properties
- toolstring weight
- cable type
- temperature profile
- wellbore pressure
- logging speed.

All these effects may differ from one well to another, so the depth corrections required also differ. Because of the number of factors involved, the corrections can be applied through a numerical model.

Logging down

Any short element of cable that is spooled off the winch drum as a tool is lowered downhole takes up a tension sufficient to support the weight of the tool in the well plus the weight of the cable between the winch and the tool, minus any frictional force that helps support the tool and cable. This prestretched cable passes the IDW device and its length is thus measured in the stretched condition. When this element of cable is downhole, the tension at the surface can be quite different. However, the tension on this element remains the same because it is still supporting the weight of the tool plus the weight of the cable between itself and the tool minus the frictional force.

If it is assumed that the frictional force is constant and that temperature and pressure do not affect the cable length, the tension on the cable—and thus the cable length—stays constant as the tool is lowered in the hole. Considering that all such elements remain at constant length once they have been measured, it follows that the down log is on depth. This means that the encoder-measured depth incorporates the stretched cable length, and no additional stretch correction is required.

Logging up

When the tool reaches the bottom of the well, the winch direction is reversed. This has the effect of inverting the sign of the frictional component acting on the tool and cable. In addition, if a caliper is opened, the magnitude of the frictional force can change. As a result, the cable everywhere in the borehole is subject to an increase in tension, and thus an increase in stretch.

For the surface equipment to track the true depth correctly, a delta-stretch correction must be added to compensate for the friction change (Fig. 4). Once the correction has been applied, the argument used while running in hole is again applicable, and the IDW correctly measures the displacement of the tool provided there are no further changes in friction.[‡]

Deviated wells

In deviated wells, the preceding depth analysis applies only to the vertical section of the well. Once the tool reaches the dogleg, lateral force from the wellbore supports part of the tool weight. The tool is thus shallower than the measured depth on surface; i.e., the recorded data appear deeper than the actual tool position. This is commonly referred to as tool float.

Correction modeling

Correction modeling software estimates the delta-stretch correction to be applied at the bottom of the well, as well as the expected tool re-zero depth upon return to the surface. This software can be used to correct the depth after logging. Contact your local Schlumberger representative for more information.

[‡]The main assumptions remain that the friction is constant (other than the change due to reversal of direction of cable motion), and that temperature and pressure effects on the cable may be ignored.

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Platform Express

Overview

Platform Express* integrated wireline logging technology employs either the AIT* array induction imager tool or High-Resolution Azimuthal Laterolog Sonde (HALS) as the resistivity tool. The Three-Detector Lithology Density (TLD) tool and Micro-Cylindrically Focused Log (MCFL) are housed in the High-Resolution Mechanical Sonde (HRMS) powered caliper. Above the HRMS are a compensated thermal neutron and gamma ray in the Highly Integrated Gamma Ray Neutron Sonde (HGNS) and a single-axis accelerometer. The real-time speed correction provided by the single-axis accelerometer for sensor measurements enables accurate depth matching of all sensors even if the tool cannot move smoothly while recording data. The resistivity, density, and microresistivity measurements are high resolution. Logging speed is twice the speed at which a standard triple-combo is run.

Specifications

Measurement Specifications	
Output	HGNS: Gamma ray, neutron porosity, tool acceleration HRMS: Bulk density, photoelectric factor (PEF), borehole caliper, microresistivity HALS: Laterolog resistivity, spontaneous potential (SP), mud resistivity (R_m) AIT: Induction resistivity, SP, R_m
Logging speed	3,600 ft/h [1,097 m/h]
Mud weight or type limitations	None
Combinability	Bottom-only toolstring with HALS or AIT tool Combinable with most tools
Special applications	Good-quality data in sticky or rugose holes Measurement close to the bottom of the well

Platform Express Component Specifications

	HGNS	HRMS	HALS	AIT-H and AIT-M
Range of measurement	Gamma ray: 0 to 1,000 gAPI Neutron porosity: 0 to 60 V/V	Bulk density: 1.4 to 3.3 g/cm^3 PEF: 1.1 to 10 Caliper: 22 in [55.88 cm]	0.2 to 40,000 ohm.m	0.1 to 2,000 ohm.m
Vertical resolution	Gamma ray: 12 in [30.48 cm] Porosity: 12 in [30.48 cm]	Bulk density: 18 in [45.72 cm] in 6-in [15.24-cm] borehole	Standard resolution: 18 in [45.72 cm] High resolution: 8 in [20.32 cm] in 6-in [15.24-cm] borehole	1, 2, and 4 ft [0.30, 0.61, and 1.22 m]
Accuracy	Gamma ray: ±5% Porosity: 0 to 20 V/V = ±1 V/V, 30 V/V = ±2 V/V, 45 V/V = ±6 V/V	Bulk density: ±0.01 g/cm^3 (accuracy[1]), 0.025 g/cm^3 (repeatability) Caliper: 0.1 in [0.25 cm] (accuracy), 0.05 in [0.127 cm] (repeatability) PEF: 0.15 (accuracy[2])	1 to 2,000 ohm.m: ±5%	Resistivities: ±0.75 ms/m (conductivity) or 2% (whichever is greater)
Depth of investigation	Gamma ray: 24 in [61.0 cm] Porosity: ~9 in [~23 cm] (varies with hydrogen index of formation)	Density: 5 in [12.70 cm]	32 in [81 cm] (varies with formation and mud resistivities)	AO/AT/AF10[5]: 10 in [25.40 cm] AO/AT/AF20: 20 in [50.80 cm] AO/AT/AF30: 30 in [76.20 cm] AO/AT/AF60: 60 in [152.40 cm] AO/AT/AF90: 90 in [228.60 cm]
Outside diameter	3.375 in [8.57 cm]	4.77 in [12.11 cm]	3.625 in [9.21 cm]	3.875 in [9.84 cm]
Length	10.85 ft [3.31 m]	12.3 ft [3.75 m]	16 ft [4.88 m]	16 ft [4.88 m]
Weight	171.7 lbm [78 kg]	313 lbm [142 kg]	221 lbm [100 kg]	AIT-H: 255 lbm [116 kg] AIT-M: 282 lbm [128 kg]

[1] Bulk density accuracy defined only for the range of 1.65 to 3.051 g/cm^3

[2] PEF accuracy defined for the range of 1.5 to 5.7

[5] AO = 1-ft [0.30-m] vertical resolution, AT = 2-ft [0.61-m] vertical resolution, AF= 4-ft [1.22-m] vertical resolution

Calibration

Master calibration of the HGNS compensated neutron tool must be performed every 3 months. Master calibration of the HRDD density tool must be performed monthly.

For calibration of the gamma ray tool of the HGNS, the area must be free from outside nuclear interference. Gamma ray background and plus calibrations are typically performed at the wellsite with the radioactive sources removed so that no contribution is made to the signal. Calibration of the tool in a vertical position is recommended. The background measurement is made first, and then a plus measurement is made by wrapping the calibration jig around the tool housing and positioning the jig on the knurled section of the gamma ray tool.

Calibration of the HGNS compensated neutron tool uses an aluminum insert sleeve seated in a tank filled with fresh water. The bottom edge of the tank is at least 33 in [84 cm] above the floor, and an 8-ft [2.4-m] perimeter around the tank is clear of walls or stationary items and all equipment, tools, and personnel. The tool is vertically lowered into the tank and sleeve so that only the taper of a centering clamp placed on the tool housing at the centering mark enters the water and the clamp supports the weight of the tool.

Calibration of the HRDD density tool uses an aluminum block and a magnesium block with multiple inserts.

Tool quality control

Standard curves

The Platform Express standard curves are listed in Table 1.

Table 1. Platform Express Standard Curves

Output Mnemonic	Output Name	Output Mnemonic	Output Name
AHF10, AHF20, AHF30, AHF60, AHF90	Array induction resistivity with 4-ft [1.2-m] vertical resolution and median depth of investigation of 10, 20, 30, 60, or 90 in [25.4, 50.8, 76.2, 152.4, or 228.6 cm]	HTNP	High-resolution thermal neutron porosity
AHO10, AHO20, AHO30, AHO60, AHO90	Array induction resistivity with 1-ft [0.3-m] vertical resolution and median depth of investigation of 10, 20, 30, 60, or 90 in	MVRA	Monitoring to resistivity of the invaded zone (R_{xo}) voltage ratio
AHT10, AHT20, AHT30, AHT60, AHT90	Array induction resistivity with 2-ft [0.6-m] vertical resolution and median depth of investigation of 10, 20, 30, 60, or 90 in	NPHI	Thermal neutron porosity borehole-size corrected
ATEMP	HGNS accelerometer temperature	NPOR	Enhanced-resolution processed thermal porosity
CFGR	Gamma ray borehole-correction factor	PEF8	Formation photoelectric factor at standard 8-in [20.3-cm] resolution
CFTC	Corrected far thermal count	PEFI	Formation photoelectric factor at standard 2-in [5.1-cm] resolution
CNTC	Corrected near thermal count	PEFZ	Formation photoelectric factor at standard 18-in [45.7-cm] resolution
CTRM	MCFL hardware contrast indicator	RHO8	Formation density at standard 8-in resolution
DNPH	Delta neutron porosity	RHOI	Formation density at standard 2-in resolution
ECGR	Environmentally corrected gamma ray	RHOZ	Formation density at standard 18-in resolution
EHGR	High-resolution environmentally corrected gamma ray	RSO8	High-resolution resistivity standoff
EHMR	Confidence on resistivity standoff	RVV	MCFL vertical voltage
ERBR[*n*]	Resistivity reconstruction error	RXGR	Global current-based resistivity
ERMC	Confidence on standoff zone resistivity	RXIB	Bucking (A1) current
ERXO	Confidence on invaded zone resistivity	RXIG	Global (A0) current
E*x*SZ[*n*]	*x*S reconstruction error	RXIGIO	Global to B0 current ratio
GDEV	HGNS deviation	RXO8	Micro-cylindrically focused R_{xo} measurement at 8-in resolution
GR	Gamma ray	RXOI	Micro-cylindrically focused R_{xo} measurement at 2-in resolution
GREZ	High-Resolution Density Detector (HRDD) cost function	RXOZ	Micro-cylindrically focused R_{xo} measurement at standard 18-in resolution
GTHV	HGNS gamma ray test high voltage	RXV	R_{xo} (A0) voltage
HAZ01	HGNS high-resolution acceleration	RXVB	Bucking (A1) voltage
HCAL	Caliper to measure borehole diameter	TNPH	Thermal neutron porosity environmentally corrected
HDRA	HRDD density correction	TREF	HGNS ADC reference
HDRX	B0 correction factor	U8	Formation volumetric photoelectric factor at standard 8-in resolution
HGR	High-resolution gamma ray	UI	Formation volumetric photoelectric factor at standard 2-in resolution
HLLD	HALS laterolog deep low-resolution measurement	UZ	Formation volumetric photoelectric factor at standard 18-in resolution
HLLS	HALS laterolog shallow low-resolution measurement	*x*CQR	*x*S crystal resolution
HMIN	Micro-inverse resistivity	*x*DTH	HRDD detector dither frequency
HMINO	Micro-normal resistivity	*x*LEW	*x*S low-energy window count rate
HNPO	High-resolution enhanced thermal neutron porosity	*x*OFC	HRDD detector offset control value
HRLD	HALS laterolog deep high-resolution measurement	*x*PHV	*x*S photomultiplier high voltage (command)
HRLS	HALS laterolog shallow high-resolution measurement	*x*SFF	*x*S form factor
HTEM	Cartridge temperature	*x*WTO	*x*S uncalibrated total count rate

Operation

The HGNS section of the Platform Express toolstring must be eccentered with a bow spring. The HRMS is positively eccentered with its own caliper, giving a borehole reaction force centered on the skid face.

The resistivity tool at the bottom of the Platform Express toolstring must be run with standoffs positioned at the top and bottom of the tool. It is important that the standoff size is the same at the top and bottom so that the sonde is not tilted with respect to the borehole.

Planning for selection of the induction or laterolog tool is important. See the "Resistivity Logging" section of this *Log Quality Control Reference Manual* for more details.

Formats

There are several quality control formats for Platform Express logs.

The HGNS format is shown in Fig. 1.

- Flag track
  - This track should show a deep green coherent pattern.
- Track 1
  - CFGR is the coefficient applied to the calibrated gamma ray to take into account the borehole corrections. Normally it is between 0.5 and 1.5.
  - GDEV output from the calibrated accelerometer should be between –10° and 90°, depending on the well.
  - DNPH is the difference between the environmentally corrected porosity and the uncorrected porosity. Usually the difference is within –10 to 10 V/V.

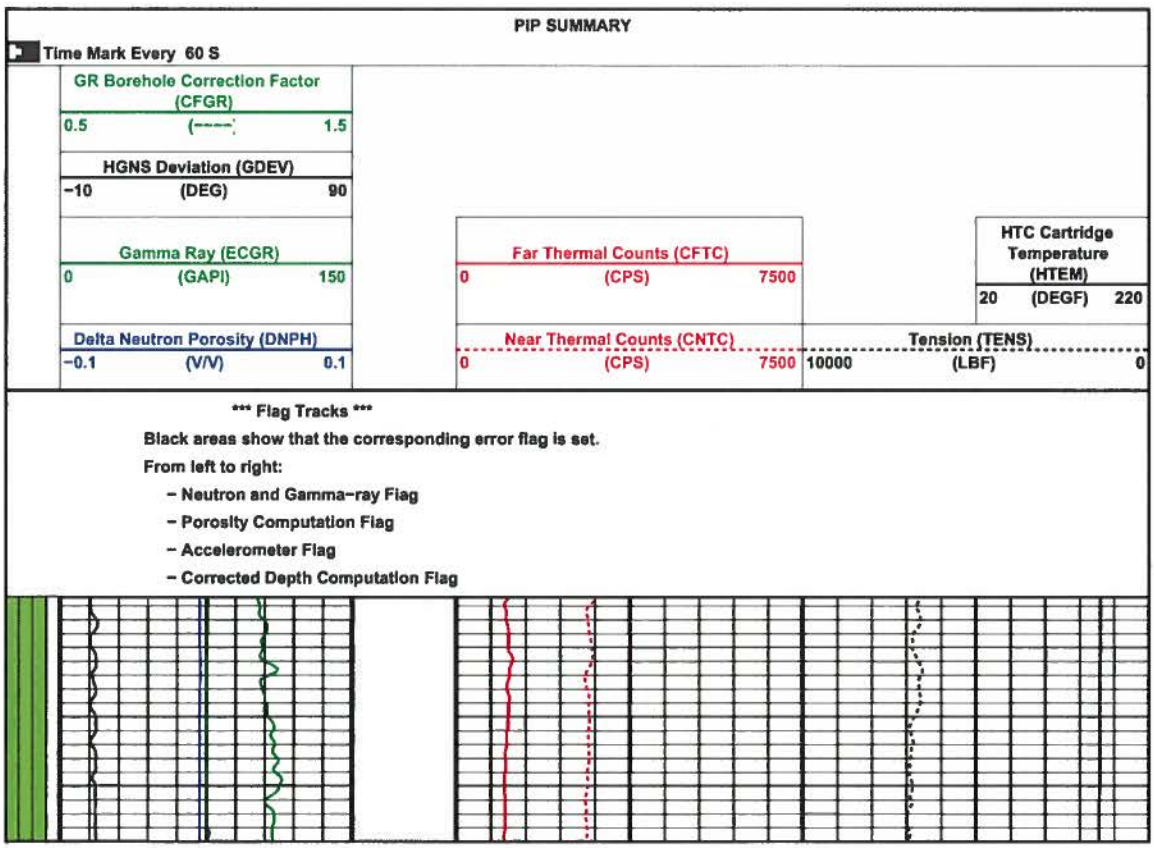

Figure 1. HGNS standard format for hardware.

The HRDD hardware format is in Fig. 2.

- Flag tracks
  - Three flag tracks aid in checking the backscatter (BS), short-spacing (SS), and long-spacing (LS) detector measurements. All bits in the tracks must show a deep green coherent color. Any other color may indicate a hardware failure.
- Tracks 1, 3, and 4
  - The xWTO total count rate varies according to the density. In general, for BS, 300,000 counts/s < BWTO < 1,000,000 counts/s; for SS, 10,000 counts/s < SWTO < 500,000 counts/s; and for LS, 1,000 counts/s < LWTO < 50,000 counts/s (cps on the logs). A large count rate change may indicate a problem with the detector.
  - The value of xSFF varies about zero (typically ±0.125%). If the form factor is higher than the permissible value, there may be a problem with the detector.
  - Variation of xCQR detector resolution is according to temperature and the presence of the logging source. Table 2 lists limits for the crystal resolution.
  - Valid count rates for xLEW are 0 to 10,000 counts/s for BS, 0 to 5,000 counts/s for SS, and 0 to 1,000 counts/s for LS. Any value outside its range may indicate a problem with the respective detector.
  - The xOFC unitless integer controls the average offset value and should ranges from 5 to 20.
  - HRDD backscatter dither frequency (xDTH) can range from 1 to 900 Hz.
  - The xPHV photomultiplier tube high voltage should be near the value given during master calibration, but it changes with temperature.

Table 2. HRDD Limits for *x*CQR Crystal Resolution

Detector	Stabilization Source Alone		With Logging Source	
	77 degF [25 degC]	257 degF [125 degC]	77 degF [25 degC]	257 degF [125 degC]
BS (BCQR)	13%	16%	12%	15%
SS (SCQR)	10%	10%	10%	10%
LS (LCQR)	9%–10%	11%	9%	11%

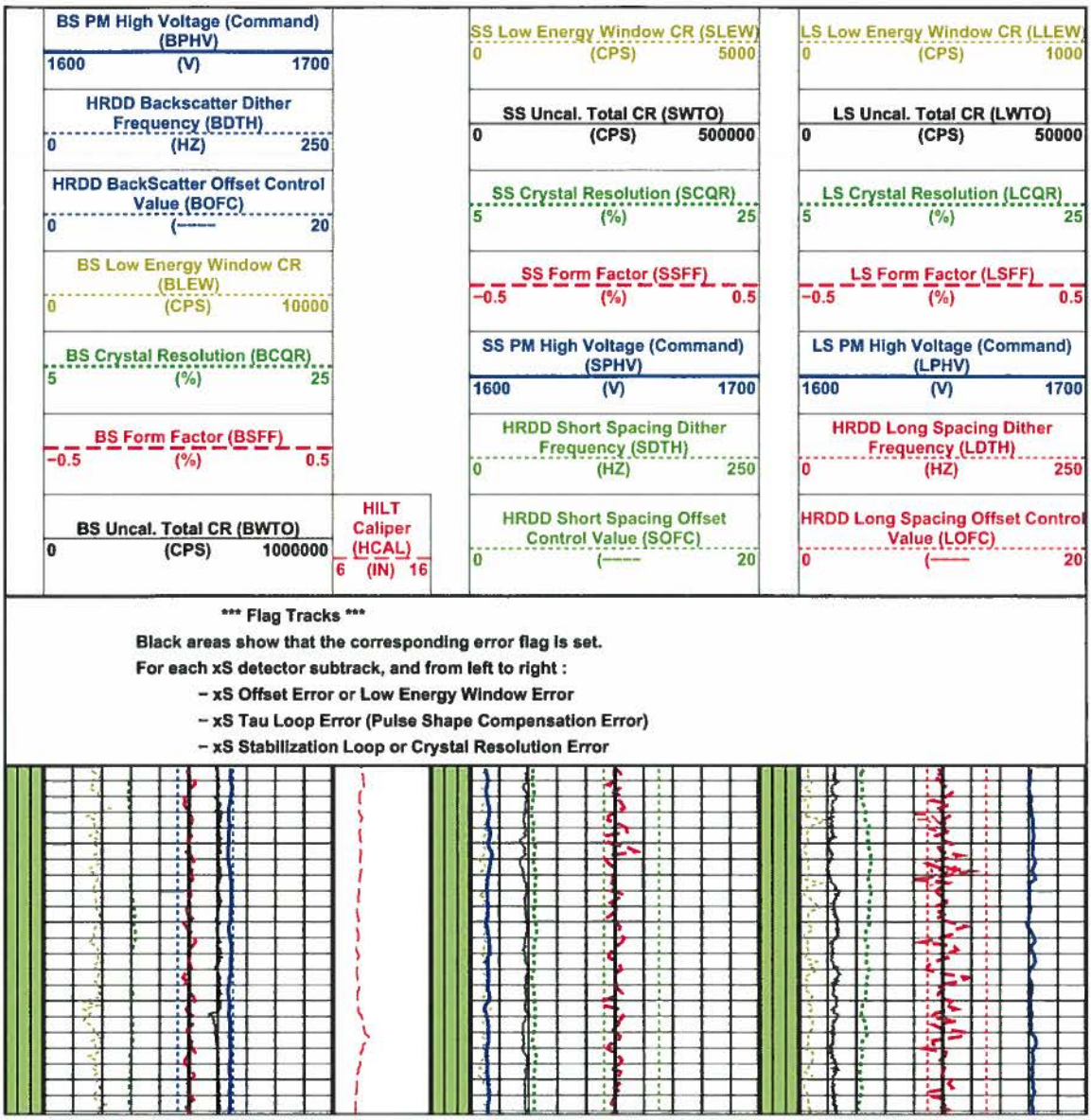

Figure 2. HRDD standard format for hardware.

The HRDD processing format is in Fig. 3.

- Tracks 1, 2, and 3
  - $ExSZ[n]$ for each detector shows how close the reconstructed count rates are to the calibrated measured count rates. Ideally, they should vary about zero. A large bias observed on these errors for one or more energy windows is generally due to a problem in the calibration, excessive pad wear, or incorrect inversion algorithm selection.
  - GREZ indicates the confidence level in the estimations done in the model. The valid range is $0 < GREZ < 25$.

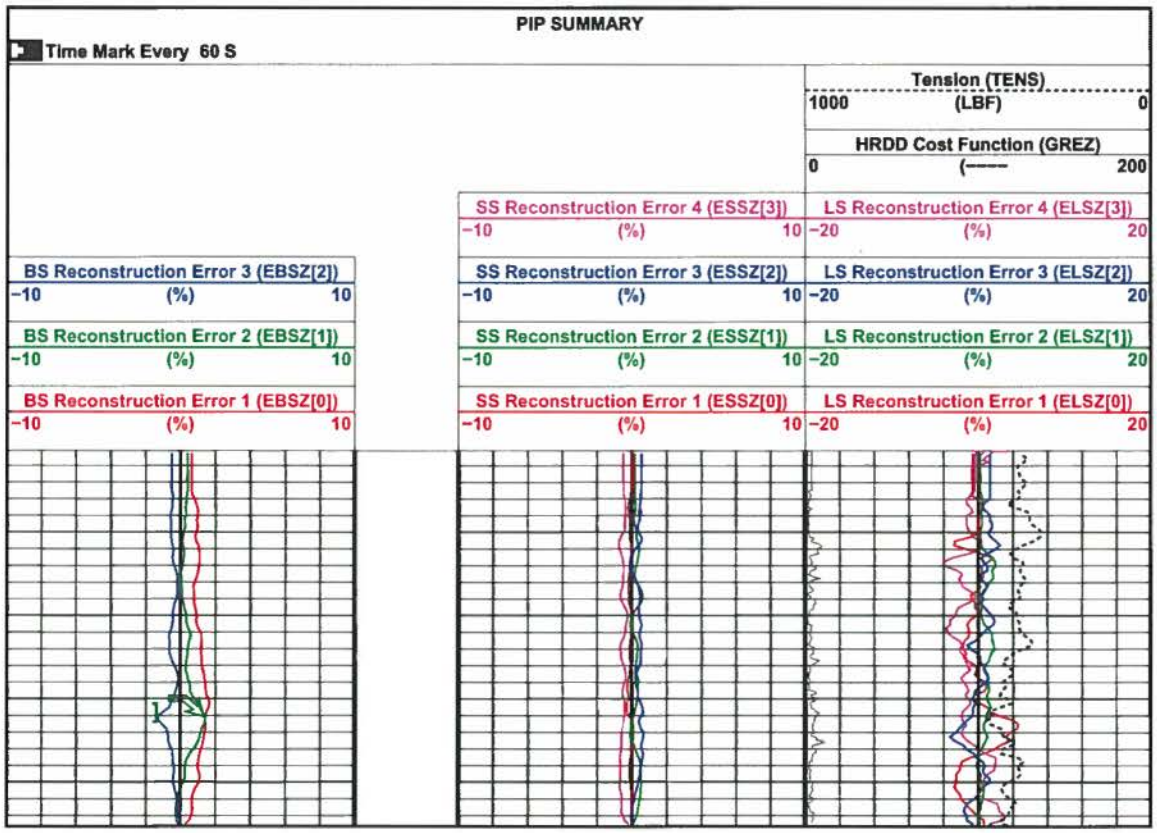

Figure 3. HRDD standard format for processing.

The MCFL hardware format is in Fig. 4.

- Flag track
  - The flag track should show a deep green coherent color. If a flag appears, it indicates a hardware malfunction.
- Track 1

  RXIB and RXIG from A0 and A1 (the guard electrodes on the tool) should range from 2 to 2,000 mA. The ratio between both curves should be constant, with the value depending on the hole size.
  - RXV between the A0 electrode and the sonde body is typically about 50 to 200 mV for R_{xo} > 10 ohm.m. It is smaller when R_{xo} < 10 ohm.m, but it should not go below 5 mV.
  - RVV between A0 and the reference electrode N should read about one-half the value of RXV (R_{xo} voltage).

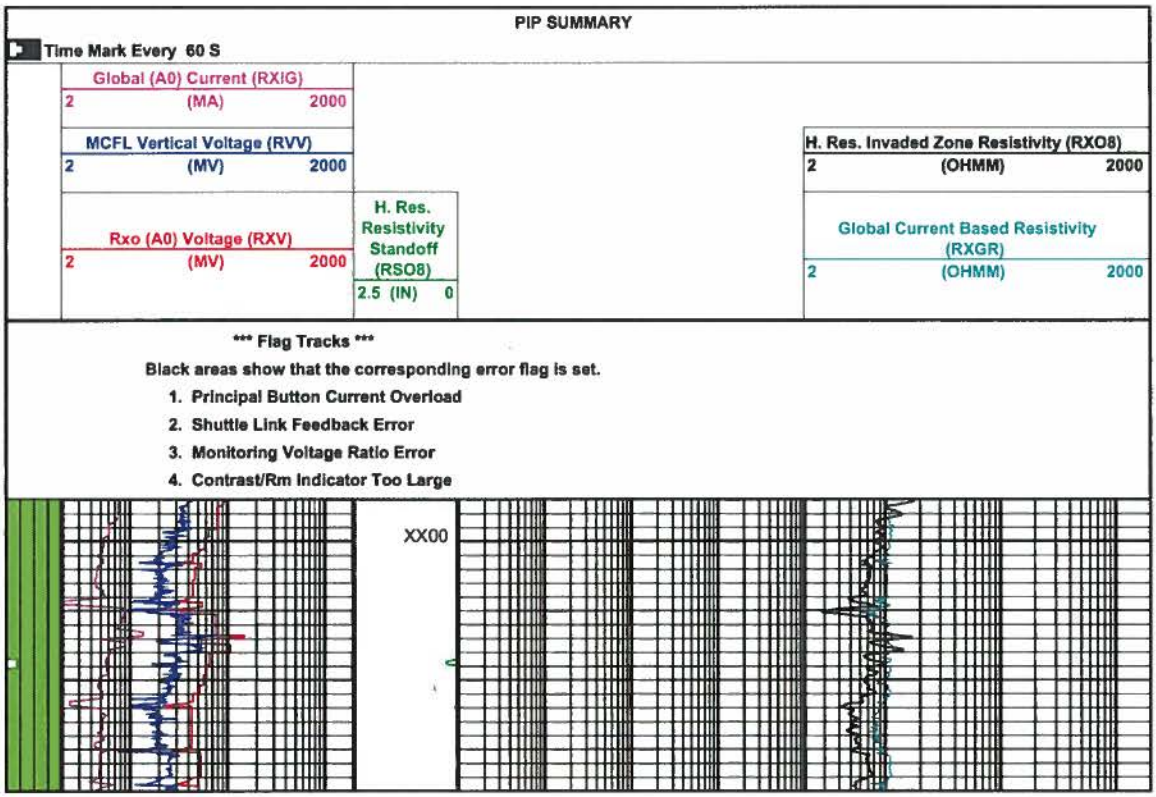

Figure 4. MCFL standard format for hardware.

The MCFL processing format is in Fig. 5.

- Track 1
  - ERBR[n] for the response of each button is used to determine how close the reconstructed measurements are to the actual ones. High error values can indicate abnormal noise level, non-homogeneous R_{xo} value, or standoff resulting from sonde tilt.
- Track 2
  - ERXO, ERMC, and EHMR confidence indicators for R_{xo}, R_{mc}, and mudcake thickness, respectively, indicate the amount of error associated with the results of the MCFL inversion. These curves should remain close to zero.
- Track 3
  - HDRX applied to the main button to match the inverted output RXOZ should range between 0.5 and 1.5.

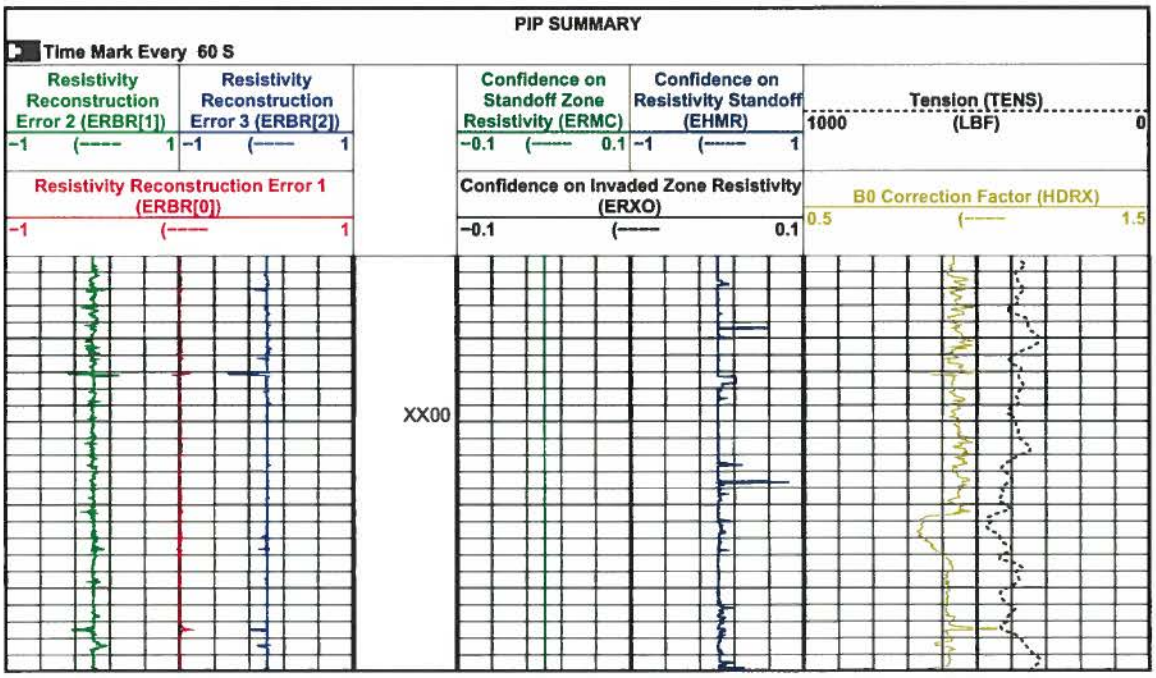

Figure 5. MCFL standard format for processing.

Response in known conditions

HGNS neutron response

The values in Table 3 assume that the matrix parameter is set to limestone (MATR = LIME), hole is in gauge, and borehole corrections are applied.

HRDD density response

Typical values for the HRDD response are in Table 4.

MCFL microresistivity response

- In impermeable zones, the R_{xo} curve should equal the induction or resistivity measurements.
- In permeable zones, the R_{xo} curve should show a coherent profile as an indication of invasion.

AIT and HALS resistivity response

- In impermeable zones, the resistivity curves should overlay.
- In permeable zones, the relative position of the curves should show a coherent profile depending on the values of the resistivity of the mud filtrate (R_{mf}) and the resistivity of the water (R_w), the respective saturation, and the depth of invasion. In salt muds, generally the invasion profile is such that deeper-reading curves have a higher value than shallower-reading curves, with deep investigation curves approaching the true formation resistivity (R_t) and shallow investigation curves approaching R_{xo}.

Table 3. Typical HGNS Response in Known Conditions

Formation	NPHI,[†] V/V	TNPH or NPOR,[‡] V/V
Sandstone, 0% porosity	–1.7	–2.0
Limestone, 0% porosity	0	0
Dolomite, 0% porosity	2.4	0.7
Sandstone, 20% porosity[§]	15.8 if formation salinity = 0 ug/g	15.1 if formation salinity = 250 ug/g
Limestone, 20% porosity	20.0	20.0
Dolomite, 20% porosity[§]	27.2 if formation salinity = 0 ug/g	22.6 if formation salinity = 0 ug/g 24.1 if formation salinity = 250 ug/g
Anhydrite	–0.2	–2.0
Salt	–0.0	–3.0
Coal	38 to 70	28 to 70
Shale	30 to 60	30 to 60

[†] After borehole correction with MATR = LIME. Refer to Chart CP-1c in Schlumberger *Log Interpretation Charts*.
[‡] After borehole correction with MATR = LIME. Refer to Charts CP-1e and -1f in Schlumberger *Log Interpretation Charts*.
[§] The reason that sandstone or dolomite with a porosity of 20% reads differently after environmental correction with MATR = LIME for different formation salinities is that the formation salinity correction is matrix dependant, and a formation salinity correction made assuming MATR = LIME is incorrect if the matrix is different. Refer to Chart Por-13b in Schlumberger *Log Interpretation Charts*.

Table 4. Typical HRDD Response in Known Conditions

Formation	RHOB, g/cm^3	PEF[†]
Sandstone, 0% porosity	2.65 to 2.68	1.81
Limestone, 0% porosity	2.71	5.08
Dolomite, 0% porosity	2.87	3.14
Anhydrite	2.98	5.05
Salt	2.04	4.65
Coal	1.2 to 1.7	0.2
Shale	2.1 to 2.8	1.8 to 6.3

[†] PEF readings are restricted to not read below 0.8

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PS Platform

Overview

The PS Platform* production services platform uses a modular design comprising the following main tools:

- Platform Basic Measurement Sonde (PBMS) for measuring pressure, temperature, gamma ray, and casing collar location
- Gradiomanometer* (PGMC) sonde for measuring the density of the well fluid and well deviation
- PS Platform Inline Spinner (PILS) for measuring high-velocity flow in small-diameter tubulars
- Flow-Caliper Imaging Sonde (PFCS) for measuring fluid velocity and water holdup and also has a dual-axis caliper.

Additional production logging tools combinable with the PS Platform system are

- GHOST* gas optical holdup sensor tool for measuring gas holdup and also has a caliper
- Digital Entry and Fluid Imaging Tool (DEFT) for measuring water and also has a caliper
- Flow Scanner* horizontal and deviated well production logging system for measuring three-phase flow rate in horizontal wells
- RST* reservoir saturation tool for measuring water velocity and three-phase holdup.

Also combinable with the PS Platform system are

- SCMT* slim cement mapping tool for a through-tubing cement quality log
- PS Platform Multifinger Imaging Tool (PMIT) for multifinger caliper surveys of pitting and erosion
- EM Pipe Scanner* electromagnetic casing inspection tool for electromagnetic inspection of corrosion and erosion
- RST reservoir saturation tool for capture sigma saturation logging, carbon/oxygen saturation logging, capture lithology identification, and silicon-activation gravel-pack quality logging.

In horizontal wells the PBMS can be replaced by the MaxTRAC* downhole well tractor system or the TuffTRAC* cased hole services tractor.

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RST and RSTPro

Overview

The dual-detector spectrometry system of the through-tubing RST* and RSTPro* reservoir saturation tools enables the recording of carbon and oxygen and Dual-Burst* thermal decay time measurements during the same trip in the well.

The carbon/oxygen (C/O) ratio is used to determine the formation oil saturation independent of the formation water salinity. This calculation is particularly helpful if the water salinity is low or unknown. If the salinity of the formation water is high, the Dual-Burst measurement is used. A combination of both measurements can be used to detect and quantify the presence of injection water of a different salinity from that of the connate water.

Calibration

The master calibration of the RST and RSTPro tools is conducted annually to eliminate tool-to-tool variation. The tool is positioned within a polypropylene sleeve in a horizontally positioned calibration tank filled with chlorides-free water.

The sigma, WFL* water flow log, and PVL* phase velocity log modes of the RST and RSTPro detectors do not require calibration. The gamma ray detector does not require calibration either.

Specifications

Measurement Specifications

	RST and RSTPro Tools
Output	Inelastic and capture yields of various elements, carbon/oxygen ratio, formation capture cross section (sigma), porosity, borehole holdup, water velocity, phase velocity, SpectroLith* processing
Logging speed†	Inelastic mode: 100 ft/h [30 m/h] (formation dependent) Capture mode: 600 ft/h [183 m/h] (formation and salinity dependent) RST sigma mode: 1,800 ft/h [549 m/h] RSTPro sigma mode: 2,800 ft/h [850 m/h]
Range of measurement	Porosity: 0 to 60 V/V
Vertical resolution	15 in [38.10 cm]
Accuracy	Based on hydrogen index of formation
Depth of investigation‡	Sigma mode: 10 to 16 in [20.5 to 40.6 cm] Inelastic capture (IC) mode: 4 to 6 in [10.2 to 15.2 cm]
Mud type or weight limitations	None
Combinability	RST tool: Combinable with the PL Flagship* system and CPLT* combinable production logging tool RSTPro tool: Combinable with tools that use the PS Platform* telemetry system and Platform Basic Measurement Sonde (PBMS)

† See Tool Planner application for advice on logging speed.

‡ Depth of investigation is formation and environment dependent.

Mechanical Specifications

	RST-A and RST-C	RST-B and RST-D
Temperature rating	302 degF [150 degC] With flask: 400 degF [204 degC]	302 degF [150 degC]
Pressure rating	15,000 psi [103 MPa] With flask: 20,000 psi [138 MPa]	15,000 psi [103 MPa]
Borehole size—min.	1 13/16 in [4.60 cm] With flask: 2¼ in [5.72 cm]	2⅞ in [7.30 cm]
Borehole size—max.	9⅝ in [24.45 cm] With flask: 9⅝ in [24.45 cm]	9⅝ in [24.45 cm]
Outside diameter	1.71 in [4.34 cm] With flask: 2.875 in [7.30 cm]	2.51 in [6.37 cm]
Length	23.0 ft [7.01 m] With flask: 33.6 ft [10.25 m]	22.2 ft [6.76 m]
Weight	101 lbm [46 kg] With flask: 243 lbm [110 kg]	208 lbm [94 kg]
Tension	10,000 lbf [44,480 N] With flask: 25,000 lbf [111,250 N]	10,000 lbf [44,480 N]
Compression	1,000 lbf [4,450 N] With flask: 1,800 lbf [8,010 N]	1,000 lbf [4,450 N]

Tool quality control

Standard curves

The RST and RSTPro standard curves are listed in Table 1.

Table 1. RST and RSTPro Standard Curves

Output Mnemonic	Output Name
BADL_DIAG	Bad level diagnostic
CCRA	RST near/far instantaneous count rate
COR	Carbon/oxygen ratio
CRRA	Near/far count rate ratio
CRRR	Count rate regulation ratio
DSIG	RST sigma difference
FBAC	Multichannel Scaler (MCS) far background
FBEF	Far beam effective current
FCOR	Far carbon/oxygen ratio
FEGF	Far capture gain correction factor
FEOF	Far capture offset correction factor
FERD	Far capture resolution degradation factor (RDF)
FIGF	Far inelastic gain correction
FIOF	Far inelastic offset correction factor
FIRD	Far inelastic RDF
IC	Inelastic capture
IRAT_FIL	RST near/far inelastic ratio
NBEF	Near beam effective current
NCOR	Near carbon/oxygen ratio
NEGF	Near capture gain correction factor
NEOF	Near capture offset correction factor
NERD	Near capture RDF
NIGF	Near inelastic gain correction
NIOF	Near inelastic offset correction factor
NIRD	Near inelastic RDF
RSCF_RST	RST selected far count rate
RSCN_RST	RST selected near count rate
SBNA	Sigma borehole near apparent
SFFA_FIL	Sigma formation far apparent
SFNA_FIL	Sigma formation near apparent
SIGM	Formation sigma
SIGM_SIG	Formation sigma uncertainty
TRAT_FIL	RST near/far capture ratio

Operation

The RST and RSTPro tools should be run eccentered. The main inelastic capture characterization database does not support a centered tool, thus it is important to ensure that the tool is run eccentered. However, for a WFL water flow log, a centered tool is recommended to better evaluate the entire wellbore region.

Formats

The format in Fig. 1 is used mainly as a hardware quality control.

- Depth track
  - Deflection of the BADL_DIAG curve by 1 unit indicates that frame data are being repeated (resulting from fast logging speed or stalled data). A deflection by 2 units indicates bad spectral data (too-low count rate).
- Track 1
  - CRRA, CRRR, NBEF, and FBEF are shown; FBEF should track openhole porosity when properly scaled.
- Track 6
  - The IC mode gain correction factors measure the distortion of the energy inelastic and elastic spectrum in the near and far detectors relative to laboratory standards. They should read between 0.98 and 1.02.
- Track 7
  - The IC mode offset correction factors are described in terms of gain, offset, and resolution degradation of the inelastic and elastic spectrum in the near and far detectors. They should read between –2 and 2.
- Track 8
  - Distortion on these curves affects inelastic and capture spectra from the near and far detectors. They should be between 0 and 15. Anything above 15 indicates a tool problem or a tool that is too hot (above 302 degF [150 degC]), which affects yield processing.

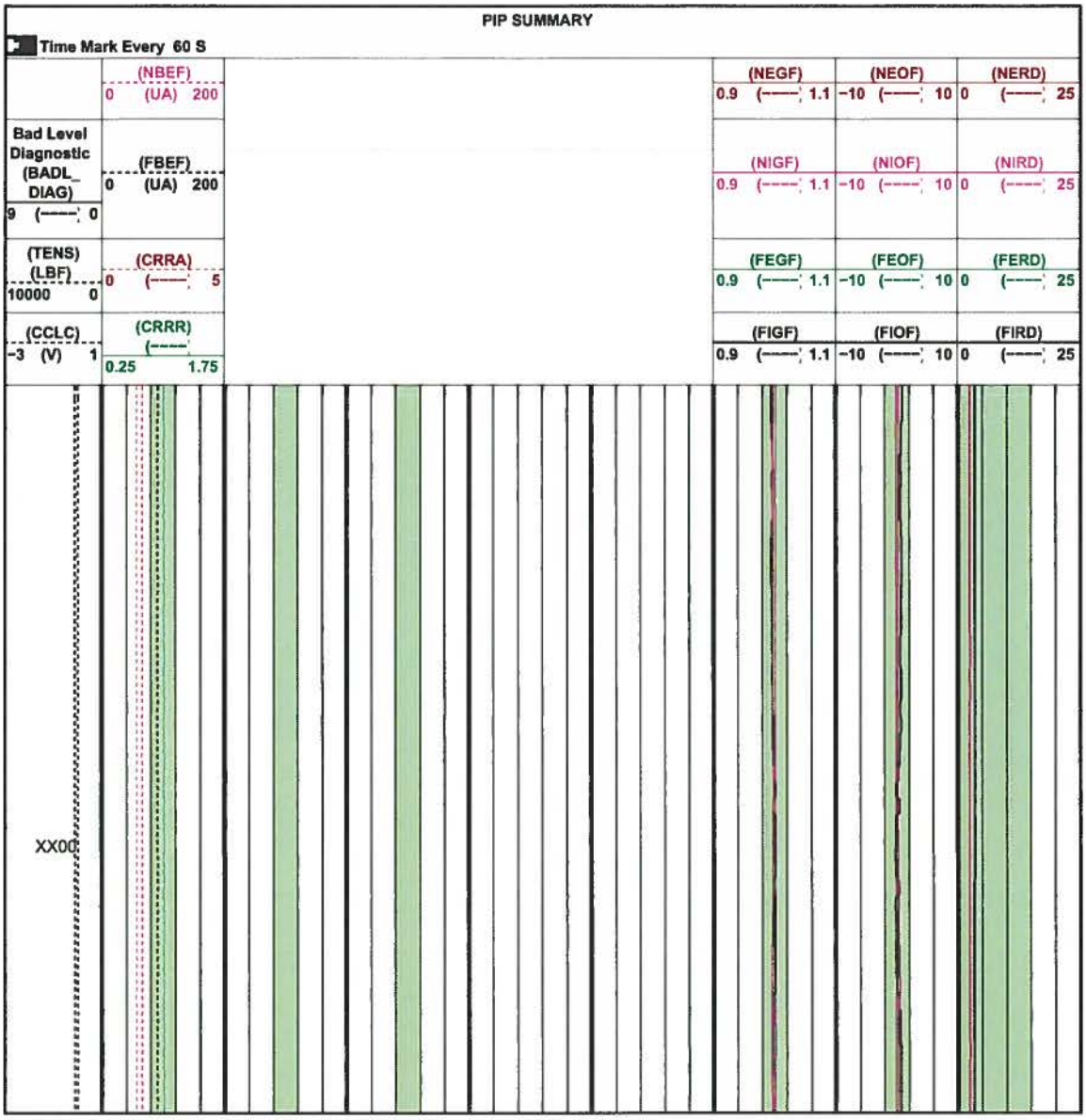

Figure 1. RST and RSTPro hardware format.

The format in Fig. 2 is used mainly for sigma quality control.

- Depth track
  - Deflection of the BADL_DIAG curve by 1 unit indicates that frame data are being repeated (resulting from fast logging speed or stalled data). A deflection by 2 units indicates bad spectral data (too-low count rate).
- Tracks 2 and 3
  - The IRAT_FIL inelastic ratio increases in gas and decreases with porosity.
  - DSIG in a characterized completion should equal approximately zero. Departures from zero indicate either the environmental parameters are set incorrectly or environment is different from the characterization database (e.g., casing is not fully centered in the wellbore or the tool is not eccentered). Shales typically read 1 to 4 units from the baseline of zero because they are not characterized in the database.

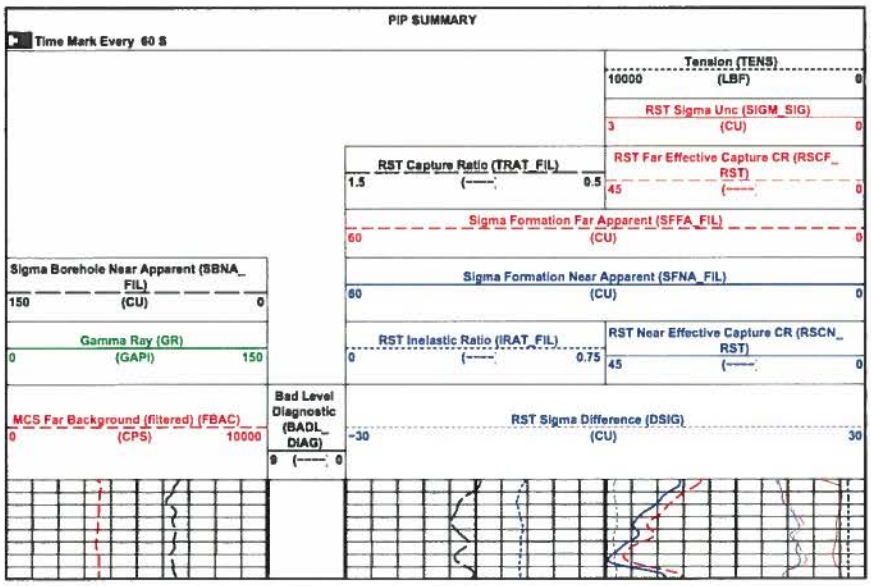

Figure 2. RST and RSTPro sigma standard format.

Response in known conditions

In front of a clean water zone, COR is smaller than the value logged across an oil zone. Oil in the borehole affects both the near and far COR, causing them to read higher than in a water-filled borehole. In front of shale, high COR is associated with organic content.

The computed yields indicate contributions from the materials being measured (Table 2).

Table 2. Contributing Materials to RST and RSTPro Yields

Element	Contributing Material
C and O	Matrix, borehole fluid, formation fluid
Si	Sandstone matrix, shale, cement behind casing
Ca	Carbonates, cement
Fe	Casing, tool housing

Bad cement quality affects readings (Table 3). A water-filled gap in the cement behind the casing appears as water to the IC measurement. Conversely, an oil-filled gap behind the casing appears as oil to the IC measurement.

Table 3. RST and RSTPro Capture and Sigma Modes

Medium	Sigma, cu
Oil	18 to 22
Gas	0 to 12
Water, fresh	20 to 22
Water, saline	22 to 120
Matrix	8 to 12
Shale	35 to 55

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Cement Bond Tool

Overview

The cement bond log (CBL) made with the Cement Bond Tool (CBT) provides continuous measurement of the attenuation of sound pulses, independent of casing fluid and transducer sensitivity. The tool is self-calibrating and less sensitive to eccentering and sonde tilt than the traditional single-spacing CBL tools. The CBT additionally gives the attenuation of sound pulses from a receiver spaced 0.8 ft [0.24 m] from the transmitter, which is used to aid interpretation in fast formations.

A CBL curve computed from the three attenuations available enables comparison with CBLs based on the typical 3-ft [0.91-m] spacing. This computed CBL continuously discriminates between the three attenuations to choose the one best suited to the well conditions. An interval transit-time curve for the casing is also recorded for interpretation and quality control.

A Variable Density* log (VDL) is recorded simultaneously from a receiver spaced 5 ft [1.52 m] from the transmitter. This display provides information on the cement/formation bond and other factors that are important to the interpretation of cement quality.

Specifications

Measurement Specifications	
Output	Attenuation measurement, CBL, VDL image, transit times
Logging speed	1,800 ft/h [549 m/h]†
Range of measurement	Formation and casing dependent
Vertical resolution	CBL: 3 ft [0.91 m] VDL: 5 ft [1.52 m] Cement map: 2 ft [0.61 m]
Accuracy	Formation and casing dependent
Depth of investigation	CBL: casing and cement interface VDL: depends on bonding and formation
Mud type or weight limitations	None

† Speed can be reduced depending on data quality.

Measurement Specifications	
Temperature rating	350 degF [177 degC]
Pressure rating	20,000 psi [138 MPa]
Borehole size—min.	3.375 in [8.57cm]
Borehole size—max.	13.375 in [33.97 cm]
Outside diameter	2.75 in [6.985 cm]
Weight	309 lbm [140 kg]

Calibration

Sonde normalization of sonic cement bond tools is performed with every Q-check. Q-check frequency is also dependent on the number of jobs run, exposure to high temperature, and other factors.

The sonic checkout setup used for calibration is supported with two stands, one on each end. A stand in the center of the tube would distort the waveform and cause errors. One end of the tube is elevated to assist in removing all air in the system, and the tool is positioned in the tube with centralizer rings.

Tool quality control

Standard curves

CBT standard curves are listed in Table 1.

Table 1. CBT Standard Curves

Output Mnemonic	Output Name
CCL	Casing collar locator amplitude
DATN	Discriminated BHC attenuation
DBI	Discriminated bond index
DCBL	Discriminated synthetic CBL
DT	Interval transit time of casing (delta-*t*)
DTMD	Delta-*t* mud (mud slowness)
GR	Gamma ray
NATN	Near 2.4-ft attenuation
NBI	Near bond index
NCBL	Near synthetic CBL
R32R	Ratio of receiver 3 sensitivity to receiver 2 sensitivity, dB
SATN	Short 0.8-ft attenuation†
SB1	Short bond index†
SCBL	Short synthetic CBL†
TT1	Transit time for mode 1 (upper transmitter, receiver 3 [UT-R3])
TT2	Transit time for mode 2 (UT-R2)
TT3	Transit time for mode 3 (lower transmitter, receiver 2 [LT-R2])
TT4	Transit time for mode 4 (LT-R3)
TT6	Transit time for mode 6 (UT-R1)
ULTR	Ratio of upper transmitter output strength to the lower transmitter output strength
VDL	Variable Density log

† In fast formations only

Operation

The tool should be run centralized.

A log should be made in a free-pipe zone (if available). Where a micro-annulus is suspected, a repeat section should be made with pressure applied to the casing.

Formats

The format in Fig. 1 is used both as an acquisition and quality control format.

- Track 1
  - DT and DTMD are derived from the transit-time measurements from all transmitter-receiver pairs. They respond to eccentralization of any of the six measurements modes and are a sensitive indicator of wellbore conditions. In a low-quality cement bond or free pipe, both readings are correct. In well-bonded sections, the transit time may cycle skip, affecting the DT and DTMD values.
  - CCL deflects in front of casing collars.
  - GR is used for correlation purposes.
- Track 2
  - DCBL is related to casing size, casing weight, and mud. As a quality control DCBL should be checked against the expected responses in known conditions (see the following section). Also, DCBL should match the VDL image readings.
- Track 3
  - VDL is a map of the waveform amplitude versus depth and it should have good contrast. It provides information on the cement/formation bond, which is important for cement quality interpretation. The VDL image should be cross checked that it matches the DCBL readings. For example, in a free-pipe section, the DCBL amplitude reads high and VDL shows strong casing arrivals with no formation arrivals. In a zone of good bond for the casing to the formation, the CBL amplitude reads low and the VDL has weak casing arrivals and clear formation arrivals.

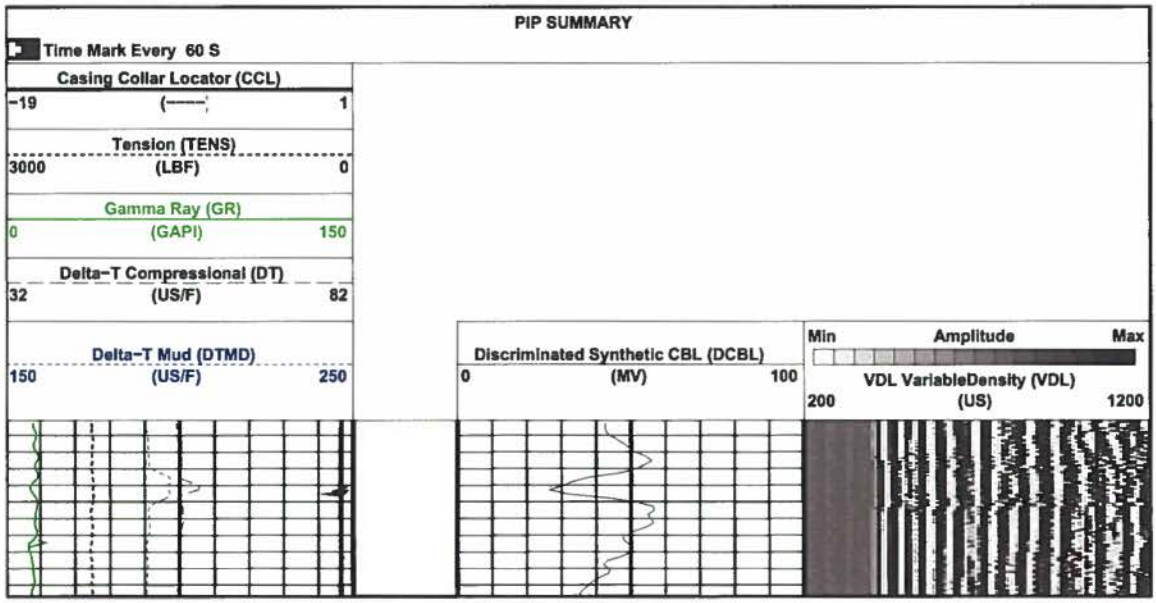

Figure 1. CBT standard format for CBL and VDL.

The format in Fig. 2 is also used both as an acquisition and quality control format.

- Track 1
  - The transit time pairs should overlay (TT1C overlays TT3C, and TT2C overlays TT4C) because these pairs are derived from equivalent transmitter-receiver spacings. In very good cement sections, the transit-time curve may be affected by cycle skipping. DT and DTMD may be also affected.
- Track 2
  - The ULTR and R32R ratios are quality indicators of the transmitter or receiver strengths. They should be 0 dB ± 3 dB, unless one of the transmitters or receivers is weak. Both curves should be checked for consistency and stability.
- Track 3
  - DATN should equal NATN in free-pipe sections. In the presence of cement behind casing and in normal conditions, NATN reads higher than DATN.
- Track 4
  - VDL is a map of the waveform amplitude versus depth that should have good contrast. It provides information on the cement/formation bond, which is important for cement quality interpretation. The VDL image should be cross checked that it matches the DCBL readings.

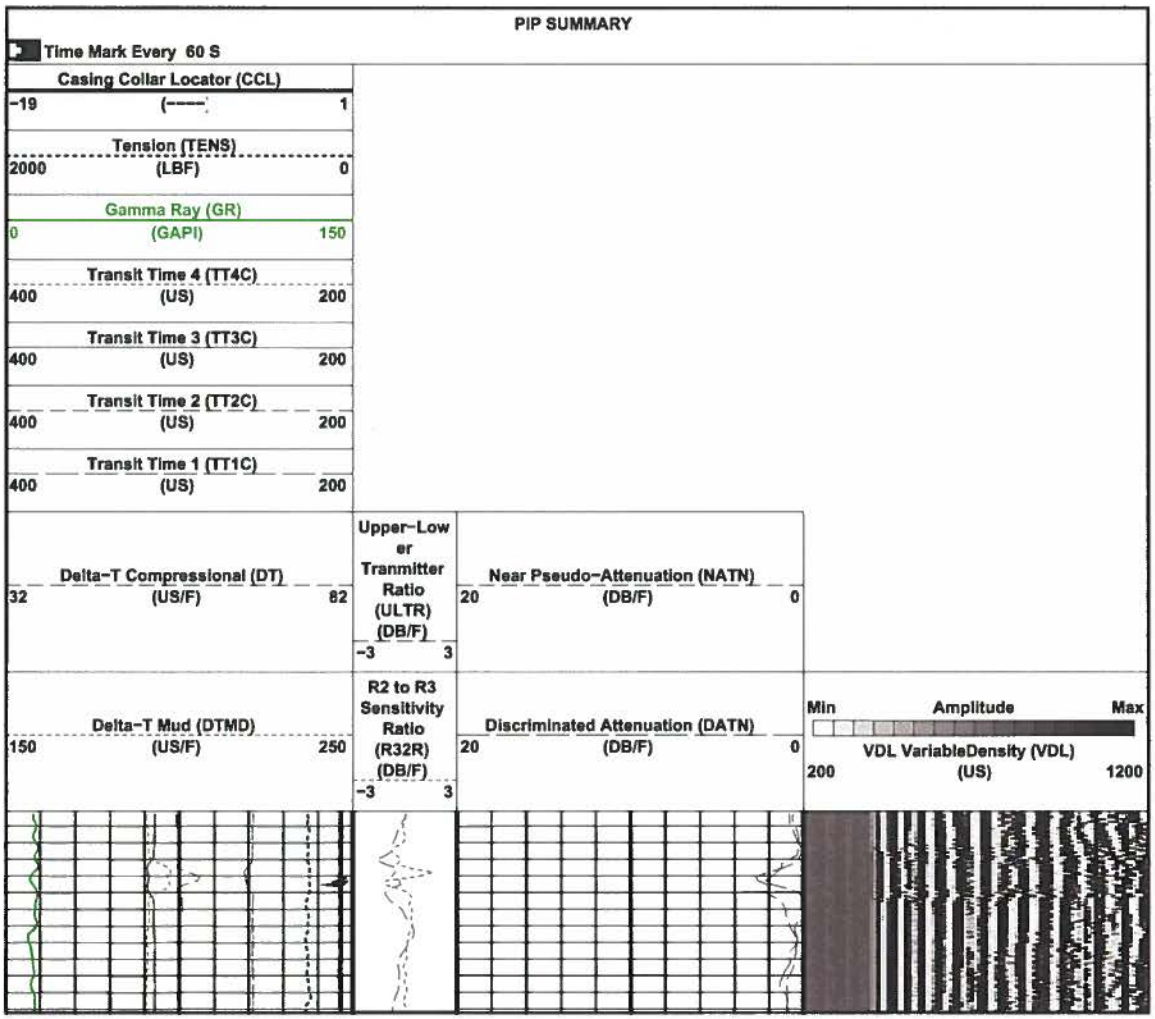

Figure 2. Additional CBT standard format for CBL and VDL.

Response in known conditions

- DT in casing should read the value for steel (57 us/ft ± 2 us/ft [187 us/m ± 6.6 us/m]).
- DTMD should be compared with known velocities (water-base mud: 180–200 us/ft [590–656 us/m], oil-base mud: 210–280 us/ft [689–919 us/m]).
- Typical responses for different casing sizes and weights are listed in Table 2.

Table 2. Typical CBT Response in Known Conditions

Casing Size, in	Casing Weight, lbm/ft	DCBL in Free Pipe, mV	TT1, us	TT2, us	TT5, us
4.5	11.6	84 ± 8	252	195	104
5	13	77 ± 7	259	203	112
5.5	17	71 ± 7	267	210	120
7	24	61 ± 6	290	233	140
8.625	38	55 ± 6	314	257	166
9.625	40[†]	52 ± 5	329	272	NM[‡]

[†] Although the CBT operates in up to 13⅜-in casing, the VDL presentation mainly shows casing arrivals where casings of 9⅝ in and larger are logged.
[‡] NM = not meaningful

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Cement Bond Logging

Overview

Cement bond tools measure the bond between the casing and the cement placed in the annulus between the casing and the wellbore. The measurement is made by using acoustic sonic and ultrasonic tools. In the case of sonic tools, the measurement is usually displayed on a cement bond log (CBL) in millivolt units, decibel attenuation, or both. Reduction of the reading in millivolts or increase of the decibel attenuation is an indication of better-quality bonding of the cement behind the casing to the casing wall. Factors that affect the quality of the cement bonding are

- cement job design and execution as well as effective mud removal
- compressive strength of the cement in place
- temperature and pressure changes applied to the casing after cementing
- epoxy resin applied to the outer wall of the casing.

The recorded CBL provides a continuous measurement of the amplitude of sound pulses produced by a transmitter-receiver pair spaced 3-ft [0.91-m] apart. This amplitude is at a maximum in uncemented free pipe and minimized in well-cemented casing. A transit-time (TT) curve of the waveform first arrival is also recorded for interpretation and quality control.

A Variable Density* log (VDL) is recorded simultaneously from a receiver spaced 5 ft [1.52 m] from the transmitter. The VDL display provides information on the cement quality and cement/formation bond.

Specifications

Measurement Specifications

	Digital Sonic Logging Tool (DSLT) and Hostile Environment Sonic Logging Tool (HSLT) with Borehole-Compensated (BHC)	**Slim Array Sonic Tool (SSLT) and SlimXtreme* Sonic Logging Tool (QSLT)**
Output	SLS-C, SLS-D, SLS-W, and SLS-E:[†] 3-ft [0.91-m] CBL Variable Density waveforms	3-ft [0.91-m] CBL and attenuation 1-ft [0.30-m] attenuation 5-ft [1.52-m] Variable Density waveforms
Logging speed	3,600 ft/h [1,097 m/h]	3,600 ft/h [1,097 m/h]
Range of measurement	40 to 200 us/ft [131 to 656 us/m]	40 to 400 us/ft [131 to 1,312 us/m]
Vertical resolution	Amplitude (mV): 3 ft [0.91 m] VDL: 5 ft [1.52 m]	Near attenuation: 1 ft [0.30 m] Amplitude (mV): 3 ft [0.91 m] VDL: 5 ft [1.52 m]
Depth of investigation	Synthetic CBL from discriminated attenuation (DCBL): Casing and cement interface VDL: Depends on cement bonding and formation properties	DCBL: Casing and cement interface VDL: Depends on cement bonding and formation properties
Mud type or weight limitations	None	None
Special applications		Conveyed on wireline, drillpipe, or coiled tubing Logging through drillpipe and tubing, in small casings, fast formations

[†] The DSLT uses the Sonic Logging Sonde (SLS) to measure cement bond amplitude and VDL evaluation.

Mechanical Specifications	DSLT	HSLT	SSLT	QSLT
Temperature rating	302 degF [150 degC]	500 degF [260 degC]	302 degF [150 degC]	500 degF [260 degC]
Pressure rating	20,000 psi [138 MPa]	25,000 psi [172 MPa]	14,000 psi [97 MPa]	30,000 psi [207 MPa]
Casing ID—min.	5 in [12.70 cm]	5 in [12.70 cm]	3½ in [8.89 cm]	4 in [10.16 cm]
Casing ID—max.	18 in [45.72 cm]	18 in [45.72 cm]	8 in [20.32 cm]	8 in [20.32 cm]
Outside diameter	3⅝ in [9.21 cm]	3¾ in [9.53 cm]	2½ in [6.35 cm]	3 in [7.62 cm]
Length	SLS-C and SLS-D: 18.7 ft [5.71 m] SLS-E and SLS-W: 20.6 ft [6.23 m]	With HSLS-W sonde: 25.5 ft [7.77 m]	23.1 ft [7.04 m] With inline centralizers: 29.6 ft [9.02 m]	23 ft [7.01 m] With inline centralizers: 29.9 ft [9.11 m]
Weight	SLS-C and SLS-D: 273 lbm [124 kg] SLS-E and SLS-W: 313 lbm [142 kg]	With HSLS-W sonde: 440 lbm [199 kg]	232 lbm [105 kg] With inline centralizers: 300 lbm [136 kg]	295 lbm [134 kg] With inline centralizers: 407 lbm [185 kg]
Tension	29,700 lbf [132,110 N]	29,700 lbf [132,110 N]	13,000 lbf [57,830 N]	13,000 lbf [57,830 N]
Compression	SLS-C and SLS-D: 1,700 lbf [7,560 N] SLS-E and SLS-W: 2,870 lbf [12,770 N]	With HSLS-W sonde: 2,870 lbf [12,770 N]	4,400 lbf [19,570 N]	4,400 lbf [19,570 N]

Calibration

Sonde normalization of sonic cement bond tools is performed with every Q-check. Scheduled frequency of Q-checks varies for each tool. Q-check frequency is also dependent on the number of jobs run, exposure to high temperature, and other factors.

The sonic checkout setup used for calibration is supported with two stands, one on each end. A stand in the center of the tube would distort the waveform and cause errors. One end of the tube is elevated to assist in removing all air in the system, and the tool is positioned in the tube with centralizer rings.

Tool quality control

Standard curves

CBL standard curves are listed in Table 1.

Table 1. CBL Standard Curves

Output Mnemonic	Output Name
BI	Bond index
CBL	Cement bond log (fixed gate)
CBLF	Fluid-compensated cement bond log
CBSL	Cement bond log (sliding gate)
CCL	Casing collar log
GR	Gamma ray
TT	Transit time (fixed gate)
TTSL	Transit time (sliding gate)
VDL	Variable Density log

Operation

The tool must be run centralized.

A log should be made in a free-pipe zone (if available). Where a micro-annulus is suspected, a repeat section should be made with pressure applied to the casing.

Formats

The format in Fig. 1 is used for both acquisition and quality control.

- Track 1
  - TT and TTSL should be constant through the log interval and should overlay. These curves deflect near casing collars. In sections of very good cement, the signal amplitude is low; detection may be affected by cycle skipping. GR is used for correlation purposes, and CCL serves as a reference for future cased hole correlations..
- Track 2
  - CBL measured in millivolts from the fixed gate should be equal to CBSL measured from the sliding gate, except in cases of cycle skipping or detection on noise.
- Track 3
  - VDL is a presentation of the acoustic waveform at a receiver of a sonic measurement. The amplitude is presented in shades of a gray scale. The VDL should show good contrast. In free pipe, it should be straight lines with chevron patterns at the casing collars. In a good bond, it should be gray (low amplitudes) or show strong formation signals (wavy lines).

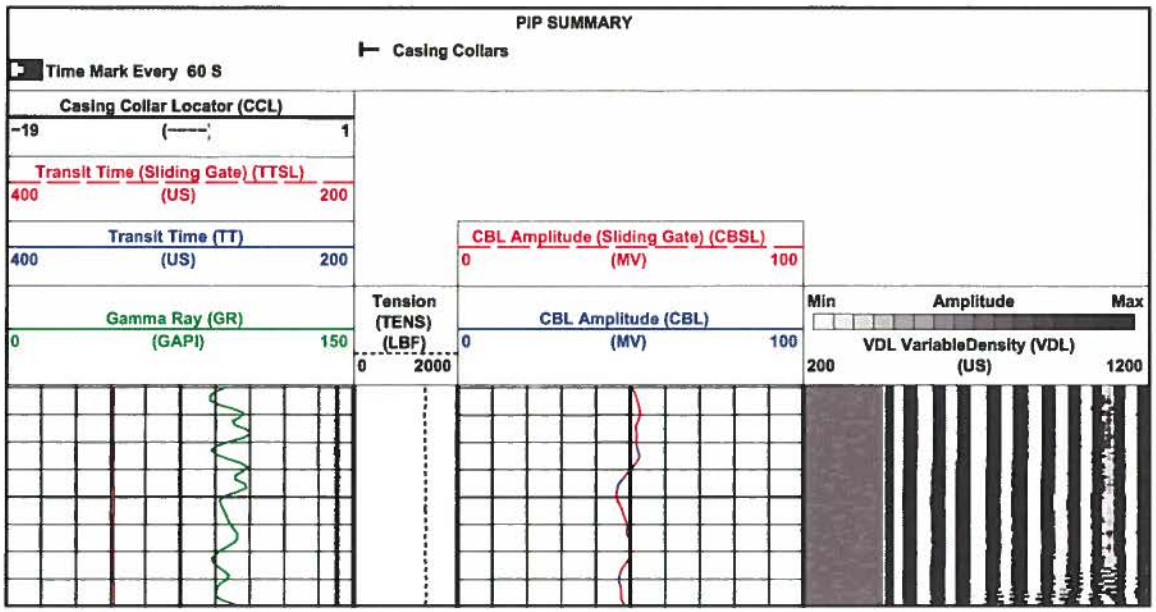

Figure 1. DSLT standard format.

Response in known conditions

The responses in Table 2 are for clean, free casing.

Table 2. Typical CBL Response in Known Conditions

Casing OD, in	Weight, lbm/ft	Nominal Casing ID, in	CBL Amplitude Response in Free Pipe, mV
5	13	4.494	77 ± 8
5.5	17	4.892	71 ± 7
7	23	6.366	62 ± 6
8.625	36	7.825	55 ± 6
9.625	47	8.681	52 ± 5
10.75	51	9.850	49 ± 5
13.375	61	12.515	43 ± 4
18.625	87.5	17.755	35 ± 4

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USI

Overview

The USI* ultrasonic imager tool (USIT) uses a single transducer mounted on an Ultrasonic Rotating Sub (USRS) on the bottom of the tool. The transmitter emits ultrasonic pulses between 200 and 700 kHz and measures the received ultrasonic waveforms reflected from the internal and external casing interfaces. The rate of decay of the waveforms received indicates the quality of the cement bond at the cement-to-casing interface, and the resonant frequency of the casing provides the casing wall thickness required for pipe inspection.

Because the transducer is mounted on the rotating sub, the entire circumference of the casing is scanned. This 360° data coverage enables evaluation of the quality of the cement bond as well as determination of the internal and external casing condition. The very high angular and vertical resolutions can detect channels as narrow as 1.2 in [3.05 cm]. Cement bond, thickness, internal and external radii, and self-explanatory maps are generated in real time at the wellsite.

Calibration

There is no calibration for the USI tool. The fluid properties measurement (FPM) of the wellbore fluid impedance (AIBK) and the fluid slowness (FVEL) is used for early input into the impedance model. The thickness of the subassembly reference plate (THBK) is also measured and output with FPM. FPM is recorded versus time while running in hole and output both as a time-depth log and as crossplots of FVEL versus depth and AIBK versus depth.

A before-survey tool check is conducted to verify basic tool operation.

Specifications

Measurement Specifications	
Output	Acoustic impedance, cement bonding to casing, internal radius, casing thickness
Logging speed	400 to 3,600 ft/h† [122 to 1,097 m/h]
Range of measurement	Acoustic impedance: 0 to 10 Mrayl [0 to 10 MPa.s/m]
Vertical resolution	Standard: 6 in [15.24 cm]
Accuracy	Less than 3.3 Mrayl: ±0.5 Mrayl
Depth of investigation	Casing-to-cement interface
Mud type or weight limitations‡	Water-base mud: Up to 15.9 lbm/galUS Oil-base mud: Up to 11.2 lbm/galUS
Combinability	Bottom-only tool, combinable with most tools
Special applications	Identification and orientation of narrow channels

† Speed depends on the resolution selected.
‡ Exact value depends on the type of mud system and casing size.

Mechanical Specifications	
Temperature rating	350 degF [177 degC]
Pressure rating	20,000 psi [138 MPa]
Casing size—min.	4½ in [11.43 cm]
Casing size—max.	13⅜ in [33.97 cm]
Outside diameter	3.375 in [8.57 cm]
Length†	19.75 ft [6.02 m]
Weight†	333 lbm [151 kg]
Tension	40,000 lbf [177,930 N]
Compression	4,000 lbf [17,790 N]

† Excluding the rotating sub

Tool quality control

Standard curves

The USI standard curves are listed in Table 1.

Table 1. USI Standard Curves

Output Mnemonic	Output Name
AIBK	Acoustic impedance fluid properties measurement (FPM)
AVMN	Minimum amplitude
AWAZ	Average amplitude
AWMX	Maximum amplitude
AZEC	Azimuth of eccentering
ECCE	Tool eccentering
ERAV	Average external radius
ERMN	Minimum external radius
ERMX	Maximum external radius
FVEL	Fluid acoustic slowness
FVEM	Fluid velocity FPM
GNMN	Minimum value of automatic gain (UPGA) in 6-in interval
GNMX	Maximum value of UPGA in 6-in interval
HRTT	Transit-time (TT) histogram
IDQC	Internal diameter quality check
IRAV	Average internal radius
IRMN	Minimum internal radius
IRMX	Maximum internal radius
THAV	Average thickness
THBK	Reference plate thickness FPM
THMN	Minimum thickness
THMX	Maximum thickness
USBI	Ultrasonic bond index
USGI	Ultrasonic gas index
WDMN	Waveform delay minimum
WDMX	Waveform delay maximum
WPKA	Waveform peak amplitude histogram

Operation

The USI tool should be run centered. The tool has centralizers in its sonde. Eccentering should be less than 0.02 in [0.508 mm] per inch of casing diameter.

In deviated wells, knuckle joints must be used along with centralizers on tools above in the string.

Cement information is critical for setting the USIT field parameters.

Formats

The format in Fig. 1 is used mainly as a quality control.

- Track 1
  - The WPKA histogram is a distribution of the waveform measured by the USIT transducer. The image scale and color represents the number of samples and their corresponding peak amplitude in binary bits.
- Track 2
  - IDQC should match the actual casing internal diameter.
  - WDMN and WDMX should be within 10 us of each other. The difference is due to casing deformation or tool eccentralization.
- Track 3
  - GNMX and GNMN are the maximum and minimum gains, respectively, in the depth frame and should range between 0 and 10 dB.
- Track 4
  - The HRTT image represents the histogram of the TT measurements on a black background, which corresponds to the positions of the peak detection window. The coherence in the log track is desired; most of the echoes should be inside the window. Measured transit times should be well within the peak detection window in a good hole. If the blue color is out of the detection windows, parameters must be adjusted on the job to the windows.

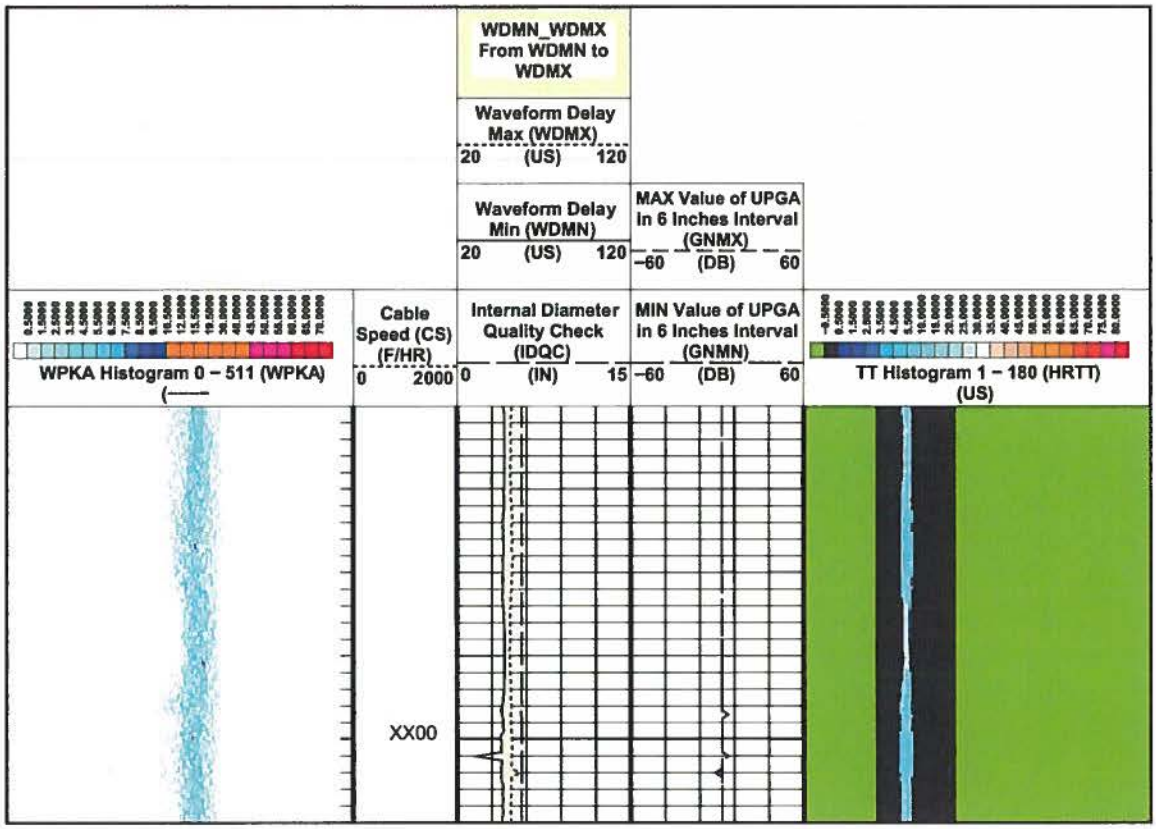

Figure 1. USIT standard format.

Response in known conditions

- The average internal radius and thickness measured by the tool should match the actual nominal internal radius of the casing.
- The expected responses in the measurement mode are listed in Table 2.

Table 2. Typical USI Response in Known Conditions

Formation	Acoustic Impedance, Mrayl
Free gas or gas microannulus	<0.3
Fresh water	1.5
Drilling fluids	1.5 to 3.0
Cement slurries	1.8 to 3.0
LITEFIL* cement (1.4 g/cm^3)	3.7 to 4.3
Neat cement (1.9 g/cm^3)	6.0 to 8.4

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